CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

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19 April 1982

FROM: The Secretariat

ICW/82/4

Consultative Group Meeting

May 24 - 26, 1982

Agenda Item 5

Attached is a copy of a letter from the Chairman of the Technical Advisory Committee to the Chairman of the Consultative Group transmitting a report by consultants engaged by TAC on the subject of Plant Nutrition (AGD/TAC:IAR/82/7).

Plant nutrition will be considered under Agenda Item 5 at the Consultative Group Meeting in May.

Attachments

Distribution:

CG Members
TAC Chairman
Dr. Cummings
TAC Secretariat
Chairman of Center Board Chairmen
Chairman of Center Directors

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TAC Members
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CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH
TECHNICAL ADVISORY COMMITTEE
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19 April 1982

Dear Mr. Baum,

I am forwarding herewith, on behalf of the Technical Advisory Committee of the CGIAR, a paper entitled "Plant Nutrition in Relation to Soil Constraints in the Developing World". This paper was prepared with the guidance of and under terms of reference provided by TAC, by Drs. Pedro A. Sanchez and John J. Nicholaides III, in response to a request by the CGIAR to TAC at its meeting in 1979, when the candidacy of the International Fertilizer Development Center came before the Group for its consideration.

The first draft of the paper was considered by the TAC at its 25th meeting in 1981. The draft was reviewed by TAC, by three independent distinguished scientists, and was furnished to the IARCs for comment prior to its finalization.

We hope that this paper will respond satisfactorily to the CGIAR request.

In reviewing the final draft at its 27th meeting, TAC gave its endorsement to the approach taken in the report in calling attention to the broader concerns regarding plant nutrition research in the context of related soil constraints in the various agro-ecological regions, and reiterates the high importance of this factor in achieving the needed levels of agricultural productivity. The IARCs, and several other institutions, international and national, are active in this field. TAC supports the continuation of such activities and would be ready to consider the needs for accelerated programmes of the IARCs in this field as part of its overall consideration of the programme and budget proposals of the Centres in the context of this report and in relation to the other priorities and demands of the system. TAC supports the cooperation which several IARCs have with IFDC and other plant nutrition research institutions and encourages continued support to such activities as a valuable complement and enhancement of the work of the IARCs in this field.

../.

Mr. Warren C. Baum
Chairman CGIAR
1818 H Street, N.W.
Washington, D.C. 20433
U.S.A.

TAC commends the attached report for its comprehensive and its careful analysis of priorities. TAC recognized the importance of the issues concerned and recognized the value and need for better coordination and strengthening of efforts in this field. TAC has been informed of the proposal under study by an independent group for the establishment of an International Board for Soil Resource Management (IBSRAM). It welcomes the prospect of support from the Australian Development Assistance Bureau (ADAB) and perhaps other agencies for further elaboration and development of the IBSRAM proposal, which would have a significant bearing on this topic. TAC is convinced that further research in plant nutrition will play an important role in agricultural intensification in the less favourable environments of the developing world. At the same time, it accords higher priority in the CGIAR context, to research in this field in the existing IARCs over support by the CGIAR for a new and separate initiative in the field.

While TAC does not recommend a new initiative by the CGIAR in this field, it commends the report to the CGIAR for careful study and consideration, calling attention to the value of this wide range of activities discussed therein which deserve continued support. In addition to distribution of the full report within the CGIAR, TAC proposes to reproduce the report, probably with the deletion of the portions of the last chapter on alternative action recommendations which are addressed primarily to the CGIAR, for distribution to a wider public audience.

Very truly yours,

Ralph W. Cummings

Ralph W. Cummings
Chairman TAC

AGD/TAC:IAR/82/7
Restricted

THE CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

TECHNICAL ADVISORY COMMITTEE

PLANT NUTRITION IN RELATION TO SOIL CONSTRAINTS IN THE DEVELOPING WORLD

(Report of the TAC Consultants)

TAC SECRETARIAT
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
March 1982

PLANT NUTRITION IN RELATION TO SOIL CONSTRAINTS IN THE DEVELOPING WORLD

Working paper prepared for TAC by

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I. SUMMARY

On May 10, 1980 the authors were asked by TAC to undertake a study on plant nutrition research for consideration by TAC/CGIAR. The purpose of the study is to assess the present status and efforts on plant nutrition research as to their degree of adequacy and whether additional efforts in this field should be considered by the CGIAR system. Considering the several recent worldwide priority assessment studies with major inputs from developing countries, the authors have given emphasis to synthesizing the above findings in terms of research needs, developing a research framework for action, and suggesting three approaches to TAC. The highlights of our findings are:

1. Food production in developing countries will be more heavily dependent on improved plant nutrition through added fertilizer inputs over the next 20 years than during the past two decades. Estimated reserves of the plant nutrients in soils, deposits of phosphorus, potassium and sulfur, and feedstocks for producing nitrogen fertilizers are generally adequate to cover expected needs. Uneven distribution and development of feedstock nitrogen sources, phosphorus and potassium deposits among countries or regions, as well as rising costs, pose significant limitations.

2. Current estimates indicate that approximately 46% of the N, P and K accumulated by the world's crops comes from the release of soil reserves, 40% from inorganic fertilizers and a small proportion from organic fertilizers, biological nitrogen fixation and atmospheric deposition. As nutrient demands are increased by intensified crop production while the amounts of nutrients released from soil reserves remain relatively constant or decrease, the need for additional nutrients from other sources becomes evident.

3. Inorganic fertilizers have made a major contribution to food production in the developing countries. Approximately 29% of the yield increase of cereals in developing countries over the last 30 years has been attributed to the use of inorganic fertilizers. Projections indicate that this proportion will increase as most of the additional crop nutritional needs worldwide will be met by inorganic fertilizers and biological nitrogen fixation. Increasing the efficiency of fertilizer use also will involve careful attention to the use and management of organic manures, crop residues and biological nitrogen fixation. The increasing demand on dung and crop residues for fuel, however, is likely to limit their availability as plant nutrient sources.

4. Plant nutrition constraints, in practice, cannot be separated from other soil-related constraints. The efficiency of utilization of fertilizers and amendments, biological nitrogen fixation and other nutritional components is so dependent on soil constraints that it is difficult to consider "plant nutrition" as an isolated "factor." Examples of such constraints are soil acidity, surface soil crusting, moisture limitations and erosion hazards. Other related constraints include inadequate soil inventories, insufficient knowledge of fertilizer marketing and limited technology transfer processes. Consequently, the authors found it necessary to broaden the original terms of reference to include soil-related constraints.

5. Seven major assessment studies have been conducted during the last six years to identify priority research areas on plant nutrition-related research. Over 300 scientists and administrators from more than 50 countries provided input in identifying such priorities. Participants included members of IARC's and several of the studies had the sponsorship of various CGIAR donors. A clear consensus developed with respect to the major problems, and the desirability of specific focus along agroecological zones.

6. Thirty-two research components were identified from the assessment studies. Five components relate to resource appraisal, three to overcoming soil stress factors, five to alleviating nutritional constraints, five to better utilizing biological resources, four to alleviating soil physical constraints, six to improving farming systems and four to technology transfer needs.

7. Five major agroecological zones, the humid tropics, semi-arid tropics, acid savannas, wetlands and the steeplands were identified as the regions requiring more attention. These zones represent the regions of the developing world where soil-plant nutrition constraints are expected to exert greater pressures on production increases, as well as endangering the deterioration of the land resource base. Plant nutrition aspects in irrigated farming systems were recognized as important.

8. The priority research components were arranged along the five agroecological zones according to several criteria, including research needs, impact over short and long terms, relative magnitude of cost, ease of transfer, expected payoff and present capabilities. A suggested research framework was developed as an agroecological zone x research component matrix.

9. The present efforts on major soil-plant nutrition research for developing countries were identified and discussed briefly. Although it was concluded that, with certain exceptions, soil-plant nutrition research is not a neglected area, many of these efforts are not conducted in a sufficiently coordinated manner to produce maximum benefits and adequate interchange of information.

10. The findings were then examined in relation to TAC/CGIAR objectives, particularly the 1979 Priorities Paper. It was concluded that the present efforts and their geographical distribution are clearly insufficient to provide a reasonable degree of certainty that technology for alleviating soil-plant nutrition constraints will be adequately developed and transferred to permit continuing increases of sufficient magnitude in food production. An international effort is needed in order to overcome this gap.

11. The authors also consider that the issue of location specificity should be brought into focus in terms of soil-plant nutrition research. The suggested research framework encompasses the kinds of problems that are generally encountered through one or more of the agroecological zones. The degree of expression of these problems is indeed location specific, but the kinds of problems are of international relevance.

12. The authors suggest that TAC initiate actions designed to better coordinate and strengthen international research on soil-plant nutrition in order to: a) Increase the efficiency of plant nutrient inputs; b) increase and stabilize food production in marginal areas of the developing countries with emphasis on rainfed areas; c) conserve the land resource base, particularly in the priority agroecological zones.

13. The International Fertilizer Development Center plays a pivotal and unique role in developing technology for improved fertilizer utilization efficiencies in the third world. IFDC's clear mandate, sense of urgency, quality of staff, research and training mix and good rapport with developing country institutions is consistent with other IARC's. Continuation of the IFDC to complement the plant nutrition research efforts of the IARC's is assumed. The IFDC issue is regarded as vital, though separate, from the three institutional approaches presented for TAC's consideration.

14. Three institutional approaches are presented for TAC consideration:

#1) Strengthening the soil-plant nutrition research in the existing IARC's and establishing a network among those conducting such research. Suggestion was made that donors be encouraged to strengthen and continue similar ongoing pertinent activities of national, bilateral, and other international programs.

#2) Develop a coordinating and catalytic center to foster soil-plant nutrition research, particularly in national and international institutes. This implies inclusion of the measures proposed in approach #1. Such a center would have a small secretariat of highly qualified staff to perform service and coordination functions.

#3) Create a full-fledged international institute on soil-plant nutrition research with emphasis on rainfed systems.

Given the advantages and limitations of each alternative, the authors consider approach #2 as the most appropriate one.

II. INTRODUCTION

A. Importance of Plant Nutrition to World Food Production

Plant nutrition can be defined as the portion of biology that deals with the factors affecting the supply and use of the elements essential for plant growth and development (Table 1). Within the context of CGIAR objectives, the principal concerns center on the nutrition of plant species that directly or indirectly provide the basic food sources in developing countries and the constraints affecting the utilization of such nutrients.

Plant nutrition is one of the key factors affecting world food production. The crops that feed present and future populations depend on adequate nutrition for sustained yields. Nutrients released from the soil, with very few exceptions, need to be supplemental with external inputs in most farming systems. Nutrient reserves in soils are exhaustible and need to be replenished in order to maintain productivity. The different sources of plant nutrients, the interactions among them and the efficiencies with which they are utilized are major practical concerns.

Much of the current emphasis focuses on the contribution of inorganic fertilizers. Nearly 75% of the food production increases in the developing countries since 1950 have been due to increasing yields per hectare. The use of inorganic fertilizers has been the most important technological factor, contributing approximately 50% of these yield increases (von Peter, 1980). The aggregate use of fertilizers in developing countries, unfortunately, is low. Currently, the developing countries use only 27% of the world's inorganic fertilizers to produce 28% of the world's cereal grain, yet farm 60% of the world's land planted to cereal and contain 73% of the world's population (FAO, 1980a).

Table 2 shows the estimated contribution of fertilizers to cereal grain production in three developing regions. The percent increase in production due to fertilizer use averaged 29%. Due to the limited land area where fertilizers were applied, their overall contribution to cereal crop production averaged only 15%. Increasing the cultivated area that is fertilized, therefore, is also an important consideration.

The World Bank (1979) has estimated that about 50% of all food production increases in the next 20 years in developing countries will be achieved through increased fertilizer use along with other associated agricultural inputs. Inorganic fertilizer use in the developing countries is projected to increase through the year 2000 at a faster rate than at present (IFDC/UNIDO, 1978; World Bank, 1979). The latter report stated that

> "Undoubtedly the increased use of fertilizer is the most important way to increase crop production and help developing countries become self-sufficient in food production." However, "it is unlikely that the overall fertilizer deficit and hence food production will improve to a satisfactory level unless there is a major attack on the constraints which prevent fertilizer use." (World Bank, 1979).

Table 1. The functions and compounds of the essential mineral nutrients occurring in plants.

Element	Probable functions	Examples of compounds
MACRONUTRIENTS:		
Nitrogen	Major metabolic importance as compounds	Amino acids (proteins), purines, pyrimidines (nucleic acids), amines, alkaloids, ureides, amino sugars, flavins and other coenzymes, porphyrins, chlorophyll
Phosphorus	Energy transfer, structural	Sugar phosphates, ATP, GTP, etc., nucleic acids, coenzymes, phytic acid, phospholipids, acetyl phosphate, phosphoenol pyruvate, coenzyme A, thiamine pyrophosphate
Potassium	Osmotic relations, protein conformation and stability, stomata, membranes and pH control	Probably occurs predominantly in the ionic form
Magnesium	Enzyme activation, pigments and ribosomal stability	Chlorophyll
Calcium	Enzyme activation, cell walls	Calcium pectate, calcium phytate, calcium carbonate
Sulphur	Active groups in enzymes and coenzymes	Cysteine, cystine, glutathionine, methionine, S-adenosyl methionine, thio-glucosides, polysaccharide sulphates (agar), lipoic acid, coenzyme A, thiamine, adenosine phosphosulphate, sulpholipids
MICRONUTRIENTS:		
Iron	Active groups in enzymes and electron carriers	Cytochromes, ferrodoxin, catalase, porphyrin synthesis, nitrogenase, nitrate, nitrite and sulphite reductases, ferritin
Copper	Enzymes, photosynthesis	Polyphenol oxidase, amine oxidase, plastocyanin
Manganese	Photosynthesis, carboxylic acid metabolism	Manganin
Molybdenum	Nitrogen fixation and nitrate reduction	Nitrate reductase, nitrogenase
Zinc	Enzymes	Carbonic anhydrase
Boron	Sugar transport, co-ordination with phenols	Borate ion; no naturally-occurring organic compound established with certainty

Table 1. (continued)

Element	Probable functions	Examples of compounds
Cobalt	Nitrogen fixation	Vitamin B_{12} in nitrogen-fixing micro-organisms only
Silicon	Structural	Hydrated silicon dioxide
Sodium	Enzyme activation	
Chlorine	Photosynthesis (as Cl-), also in compounds	Chlorinated indoles, alkaloids

Adapted from: Hewitt and Smith (1975).

Table 2. Estimated contribution of fertilizer to cereal grain production in developing market economies, 1948-1952 to 1972-1973.*

Region	Increase in total annual cereal production	Estimated increase due to fertilizers		Estimated total production due to fertilizers (1972-1973)
	------ million tons ------		%	%
Asia	81.5	26.2	32	15
Latin America	40.5	10.8	27	16
Africa	12.4	2.5	20	6
Total	134.4	39.5	29	15

*Calculated from IFDC/UNIDO (1978).

As important as inorganic fertilizers are to world food production, their increased use is only a partial answer. Energy limitations and the increased fertilizer production costs exert major influence on the inorganic fertilizer picture. In the case of N, which is the most energy-consuming and expensive to produce, not only must alternate hydrocarbon foodstocks be found, but also increased efficiencies of N fertilizer use must be developed. Additionally, closer examination of organic and biological sources of N must be undertaken.

Just as inorganic fertilizers are not the only factors limiting adequate plant nutrition, seldom is plant nutrition the only factor limiting crop production. Crop yield and quality are a function of crop, soil, climate and management, with each factor encompassing numerous variables. Even when plant nutrition factors are optimum, including the most judicious use of inorganic fertilizers, if any other factor, such as water, is more limiting and not alleviated, crop production will suffer.

Water stress is one of the most frequently limiting factors affecting the utilization of plant nutrients. An additional 50 million ha.of irrigated agriculture are expected to be added by 1990, and irrigation water use will double by 2000 (Levine et al., 1979). Currently, 201 million hectares, 14% of the world's cropland are irrigated (FAO, 1980a). Two-thirds of the present irrigated land is planted primarily to rice, with the remaining third to cotton, sugar beets, sugarcane, fruits and other grains (NAS, 1977 a,b). Much of this irrigated land is not in the arid areas, but in the subhumid and humid regions of the world, mainly in Asia (NAS, 1977 a,b). The developing countries hold 73% of the world's irrigated hectarage, with Asia accounting for 57% and the Near East, Latin America and Africa having 9%, 6% and 1%, respectively (FAO, 1980a). India, China and Pakistan alone account for 49% of the world's irrigated land and 66% of the developing countries' irrigated agriculture (FAO, 1980a).

The impact of irrigation on food production is of major dimension. For example, in India grain production on rainfed agriculture averages about 400 kg/ha, while that produced by irrigated agriculture averages 2150 kg/ha (Levine, et al., 1979). Although no statistics are available, it is safe to assert that a large proportion of fertilizers used in developing countries is used on irrigated land as well as on plantation agriculture. It is obvious, therefore, that during the next decades improved efficiencies of plant nutrients must play a key role in food production increases in irrigated agriculture, especially in the more heavily populated countries of Asia and the Near East.

Water resource development, however, is likely to be insufficient to make a significant impact on increased food production in most developing countries of Africa by 2000 (Levine et al., 1979), Latin America and parts of Asia. In these areas, rainfed agriculture will be the main contributor to food production increases (Levine et al., 1979). In addition, the high investment cost of irrigation (averaging U.S.$8,000/ha if water is stored) make it particularly necessary alleviate several soil constraints to insure that irrigation water be used effectively (Levine et al., 1979). Improved plant nutrition, therefore, is expected to play a key role both in irrigated and rainfed farming systems during the next decades.

The overall importance of plant nutrition to world food production is further emphasized in the seven recent independent major studies of the world food situation conducted within the last five years. They have all stressed the critical need for overcoming constraints related to plant nutrition for increased world food production.

B. Terms of Reference

Participants of the May 1979 CGIAR meeting felt that priorities for new initiatives by the CGIAR in the field of factor-oriented research, plant nutrition research, in particular, required further assessment by the TAC (CGIAR, 1980b).

The authors of this report were asked by TAC on May 10, 1980 to undertake a study on plant nutrition research for consideration of TAC/CGIAR. In the subsequent months, several outlines for the report were proposed by TAC and by the authors and were discussed. The following plan was agreed upon by the TAC Steering Committee and the authors:

1. To develop a background paper which would address, at least generally and briefly, the following topics:

   a) The importance of plant nutrition in world food production
   b) The plant nutrient sources and use from

      -mineral and organic soil reserves
      -inorganic chemical fertilizers
      -biological nitrogen fixation, both symbiotic and non-symbiotic
      -recycling of organic residues and wastes

2. To present, against such a background, the following:

   a) Plant nutrition research priorities by major recent assessments.
   b) Grouping of the consensus plant nutrition research priorities along specific agroecological zones within the framework of short and long-term impact, magnitude of cost, ease of transfer, payoff and existing capabilities of national and international research institutions.
   c) Detailing major current involvements in addressing these plant nutrition research priorities of various institutions in developing and developed countries.

3. To suggest, against such a background, alternatives for CGIAR/TAC consideration in addressing priority plant nutrition research needs.

As one or both of the authors of this report were fortunate to have participated in the last four studies concerning plant nutrition research needs and have traveled extensively to developing and developed countries during their leadership of one of these studies, it was felt by the TAC Steering Committee and the authors that major additional travel in the development of this report would be unnecessary. A three-day visit was made to IFDC in November 1980 to augment information the authors had gathered in the course of the other studies and the present one. An interim report was submitted to the TAC Chairman on October 16, 1980. A draft of the final report then was submitted on January 12, 1981 to the TAC Chairman, who forwarded it to the TAC membership for review prior to the junior author's oral presentation of the report to the TAC on February 25, 1981 in Addis Ababa, Ethiopia at its 25th meeting. This current final report is the revision of that draft report following review by TAC and by TAC-commissioned scientists.

The TAC Priorities Paper (TAC, 1979a) and the Report of the TAC Mission to IFDC (TAC, 1979b) proved especially useful as background materials for the preparation of both the interim and final draft reports. Many other reports, articles, books and personal communications concerning plant nutrition and the world food problem were utilized in the course of this study. From these, the pertinent information has been distilled, summarized and used in the present report.

Gratitude is expressed to Drs. R. W. Cummings and J. K. Coulter, who comprised the TAC Steering Committee for this report, and to Mr. P. J. Mahler for their valuable advice and suggestions in the preparation of this report. Acknowledgement and thanks are extended to Drs. D. L. McCune, P. J. Stangel (IFDC), R. Dudal (FAO) and several North Carolina State University faculty for supplying background materials which otherwise would have been unavailable or extremely difficult to obtain. The review comments of Drs. D. Munns (Universith of California at Davis), D. Muljadi (Soils Research Institute, Indonesia), J. Velly (ORSTOM, France), D. J. Greenland and N. C. Brady (IRRI) were most helpful in improving this report.

III. PLANT NUTRIENT SOURCES AND USE

This section shall focus mainly on the primary nutrients due to their overriding importance for crop production, though the contribution of other essential nutrients to crop production is acknowledged.

Due to the lack of complete information in the literature regarding the absolute and relative contributions of major sources of primary nutrients to the world's crops, the authors have calculated gross estimates of primary nutrients supplied annually to the world's 1414 million hectares of cultivated and permanent crops (Table 3). The major sources of primary nutrients were considered to be those released in available form from soils, inorganic fertilizers, organic fertilizers, biological nitrogen fixation and atmospheric deposition. Soil release data are from authors' calculations based on uptake data by non-fertilized crops (Sanchez, 1976); inorganic fertilizer data are from IFDC/UNIDO (1978); organic fertilizer data are from data for China (Kemmler, 1979) and adjusted by dividing China hectarage by world hectarage (these organic manures do not include crop residues which have remained on harvested fields); biological nitrogen fixation and atmospheric deposition data are from Frissel (1978). Table 3 shows that nutrients released from the soil or added as inorganic fertilizers comprised most of those supplied to the world's cultivated and permanent crops.

A. Soil Reserves

Although large total amounts of reserves of essential elements are contained in the soil (Appendix Table 1), the capacity of the soil to supply them to plants is limited. It should be recognized that even the small amounts of total nutrient reserves released annually in available form to plants cannot continue to be released indefinitely without being replenished--from whatever source. Most soil N reserves are organic and small portions are mineralized slowly. Most soil P reserves in the mineral fraction are relatively insoluble forms of iron, aluminum, occluded, and calcium phosphates and only over time do small portions of some of these become available to plants. Much P is present in organic matter, but that mineralized is commonly incorporated into the solid inorganic fraction. Potassium availability from the soil in contrast, is generally governed by weathering of primary minerals.

Published data with accurate estimates of the amounts of essential elements supplied to crops solely from nutrient reserves are difficult to find. Based on calculations using primary nutrient uptake data by non-fertilized cereals, the authors were able to arrive at the following gross estimates of primary nutrients released annually to crops from mineral and organic soil reserves: 30 N, 15 P_2O_5 and 47 K_2O in kg/ha (Table 3). Overall, the amount of available primary nutrients supplied from reserves in the soil totals 92 kg/ha, while that estimated to have been applied from inorganic sources in the developing countries in 1980 was 32 kg/ha (Table 3).

Table 3. Gross estimates of primary nutrients supplied annually to the world's 1414 million hectares of annual and permanent crops.

Plant Nutrient Source	N			P_2O_5			K_2O			Primary nutrients		
	kg/ha	Total 10^6 tons	% of Total	kg/ha	Total 10^6 tons	% of Total	kg/ha	Total 10^6 tons	% of Total	kg/ha	Total 10^6 tons	% of Total
Soil release	30	42	34	15	21	38	47	66	66	92	86	46
Inorganic fertilizers	39	56	44	21	30	54	19	27	27	79	113	40
Organic fertilizers	4	6	5	3	4	8	5	7	7	12	17	6
Biological N fixation	9	13	10	0	0	0	0	0	0	9	13	5
Atmospheric deposition	6	9	7	0	0	0	0	0	0	6	9	3
Total	88	126	100	39	55	100	71	100	100	198	281	100

B. Inorganic Fertilizers

Our estimates are that inorganic fertilizers comprise 40% of the primary nutrients supplied to crops worldwide (Table 3). The World Bank (1979) estimated that inorganic sources furnish "the majority of crop nutritional needs worldwide." The bulk of crop nutritional needs on a world scale through at least 2000 are projected by World Bank (1979) to continue to be from inorganic sources, which, in addition to the primary nutrients, includes Ca, Mg, S and the micronutrients. The World Bank report indicated that in terms of cost for the individual farmer and foreign exchange for the developing nations, inorganic fertilizers will be the most important input in crop production from present through at least 2000. Indeed, FAO (1980c) reported that the developing countries' share of the imported fertilizers increased from 6% in 1972/73 to 32% in 1978/79. The developing countries' share of raw materials required in the annual production of inorganic fertilizers is expected to increase from about 28% to almost 40% between 1980 and 2000 (Appendix Table 2). Fertilizer use in LDC's will increase more than two and one-half times between 1980 and 2000 (Table 4).

1. Nitrogen. Industrially-produced N fertilizer is critical for the production of cereal grain, which is the world's major food source. Our estimates are that inorganic fertilizers furnish 44% of the annual N supplied to the world's cultivated and permanent cropland (Table 3).

World demand for N fertilizer is projected to increase from 56 million tons in 1980 to 140 million tons in 2000, with developing countries' demand increasing from 33 to 39% of the total (Table 5). World N supplies from 1980 through 2000 are expected to exceed demand by several percentage points each year, with the developing countries' production programs approaching the suggestion of an UNIDO study of group self-sufficiency in N and P fertilizers by 2000 (IFDC/UNIDO, 1978). Thus, by 2000, about 40% of the world's N production capacity may be located in developing countries.

Natural gas will continue to be the main feedstock for ammonia plants to produce N fertilizer, though its use is projected to decrease from 72% in plants built from 1980 to 1985 to 64% in 1990-2000. Coal will increase from 9 to 17% in these same years, with naptha and oil comprising the other 5 and 15%, respectively (IFDC/UNIDO, 1978). The developing countries most likely will use natural gas as a feedstock for ammonia production (Stangel, 1977). Nearly 80% of the N fertilizer will be urea or ammonium nitrate, with the remainder as anhydrous ammonia, ammonium sulfate and ammonium phosphates (IFDC/UNIDO, 1978).

The 1977 reserves and production of natural gas, petroleum and black coal in developing and developed regions of the world are presented in Appendix Table 3. The world's 1977 known reserves of petroleum and natural gas by country are shown in Appendix Table 4. From these tables, it can be concluded that ammonia feedstocks are widely distributed among both developed and developing regions, that developing countries' reserves are much greater relative to their current production rates than are those of developed countries, and that coal supplies are more than adequate for ammonia production. However, although these hydrocarbon feedstocks are available in adequate quantities, they are likely to become increasingly more expensive.

Table 4. Actual and projected fertilizer use in developing and developed countries, 1974-2000.*

Country Groups	1974	1980	1990	2000	1974	1980	1990	2000
	kg/capita				kg/hectare			
Developed	58	73	100	130	109	149	225	322
Developing	7	9	14	19	22	32	55	83

*Adapted from IFDC/UNIDO (1978).

Table 5. Estimated and projected fertilizer production and consumption or demand by developed and developing countries, 1960-2000.*

Year and Nutrient	Production			Consumption/Demand		
	World	Developed**	Developing***	World	Developed	Developing
	million tons					
1960:						
N	10.4	9.4	0.9	9.7	7.8	1.9
P_2O_5	10.0	9.2	0.7	9.8	8.9	0.9
K_2O	8.7	8.6	0.1	8.2	7.8	0.4
1970:						
N	30.2	26.1	4.1	28.7	21.0	7.7
P_2O_5	19.3	17.0	2.3	18.8	15.6	3.2
K_2O	16.7	16.1	0.6	15.5	14.0	1.5
1980:						
N				55.6	37.5	18.1
P_2O_5				30.4	22.8	7.6
K_2O				27.1	22.8	4.3
1990:						
N				92.8	58.9	33.9
P_2O_5				45.4	31.0	14.4
K_2O				41.9	33.3	8.6
2000:						
N				139.6	85.1	54.5
P_2O_5				63.9	40.6	23.3
K_2O				60.2	45.8	14.4

* Adapted from IFDC/UNIDO (1978).
** Developed countries include North America, West Europe, East Europe, USSR, Japan, Israel, South Africa, Australia and New Zealand.
*** Developing countries include those in Latin America, Asia (except Japan and Israel), Africa (except South Africa) and Oceania (except Australia and New Zealand).

2. Phosphorus. Our estimates are that inorganic fertilizers furnish 54% of the P_2O_5 supplied annually to the world's cultivated and permanent cropland (Table 3). World demand for P_2O_5 is anticipated to grow from 30 million tons in 1980 to 64 million tons in 2000, as developing countries' demand of the total increases from 25 to nearly 37% (Table 5). World production of phosphate rock by country and region are presented in Appendix Tables 5 and 6, respectively. Ample known reserves of phosphate rock exist (Appendix Table 7); in fact, rate of discovery exceeds the rate of consumption (IFDC, 1978). The quality of the deposits varies, but supplies are expected to exceed demand by several percentage points per year as several developing countries attempt to become self-sufficient in phosphate. Concentrated fertilizers shall continue to be the main P sources with diammonium phosphate (DAP), monoammonium phosphate (MPA), and triple superphosphate (TSP), comprising, respectively, 50, 30 and 20% of the total (IFDC/UNIDO, 1978). The direct application of ground or partially acidulated phosphate rock (current use estimated at 8% worldwide) could decrease the need for chemically manufactured phosphates. Phosphate fertilizers will be used more in compound fertilizers, comprising 65% and 86% of the P_2O_5 consumed in developing and developed countries, respectively, by 2000 (IFDC/UNIDO, 1978).

3. Potassium. Our estimates are that inorganic fertilizers furnish 27% of the K_2O supplied annually to the world's cultivated and permanent cropland (Table 3). World demand for K_2O will increase from 27 million tons in 1980 to 60 million tons in 2000, with developing countries' share of world demand increasing from 16 to 24% of the total (Table 5). Though ample reserves of potash exist (Appendix Table 8), most lie in a few developed countries; thus, most developing countries will have to rely on K_2O imports for the foreseeable future, although some new potash deposits have been found in Brazil, Ethiopia, Iran, Laos, Libya, Morocco, Pakistan, Peru, Poland, Thailand and Tunisia. Deposits are being mined in China and Chile, while Brazil, Jordan and Poland have exploitation plans (IFDC/UNIDO, 1978). Potash supplies should equal or slightly exceed demand in the future. However, 50-60% of the new planned potash capacity is in the USSR and, if delayed, could precipitate a tight world potash supply (World Bank, 1979).

4. N:P:K ratios. Through 2000 the developing countries are expected to maintain a nutrient ratio of 4:2:1 for $N:P_2O_5:K_2O$, while the developed countries are expected to increase the N of the 1974 ratio of 1.4:1:1 to 2.2:1:1 by 2000 (IFDC/UNIDO, 1978). Thus, from 1980 through 2000, the greater part of fertilizer growth will be in N, increasing 151% from 56 to 140 million tons. The growth of P_2O_5 and K_2O will increase 113% from 30 to 64 million tons and 122% from 27 to 60 million tons, respectively. The demand of the developing countries by 2000 is projected to be for nearly two-fifths of the N, more than one-third of the P_2O_5 and about one-quarter of the K_2O.

5. Sulfur. Sulfur supplies are expected to be more than adequate to meet fertilizer needs through 2000 and beyond (Stangel, 1977). This is due to the increasing emphasis on pollution control which will necessitate large amounts of S being recovered and disposed. This recovered S exceeds S demands by the phosphate industry and if economically feasible will be so used. Due

to the higher analysis fertilizers being used, S deficiencies are being noted more and more on a global scale (Blair et al., 1980). World production of sulfur by country in 1975 is presented in Appendix Table 9. Annual consumption of S for fertilizer production is projected to increase from 25 million tons to 65 million tons from 1980 to 2000, with a total consumption during these years of about 900 million tons or less than 20% of the reserves (Appendix Table 10) at present being used (IFDC/UNIDO, 1978).

6. Lime. Lime supplies, both calcitic and dolomitic, are expected to exceed demand through 2000, though use is not equivalent to what is required at present. Even in the United States, lime use has been essentially static at around 25 million tons per year since 1947 (Nicholaides, 1982). In the developing countries, lime use also is much less than that required. With increased research in evaluation and development of crop species and varieties tolerant to soil acidity and the consequent use of these varieties in developing countries, lime supplies in developing countries are expected to be sufficient well beyond the 21st century.

7. Micronutrients. Micronutrient supplies and demand are more site-specific, hence, information is limited. However, the generalizations can be made for B, Cl, Cu, Fe, Mn, Mo and Zn that supplies are adequate to meet demand beyond 2000. As the macroelements become less limiting to crop yields through increased and judicious use, the microelements are expected to take on increased importance in crop production.

C. Biological Nitrogen Fixation

Although biological sources undoubtedly contribute to nutrients supplied to the world's crops, the only one for which there is a reasonable estimate of its contribution is biological nitrogen fixation (BNF) through the symbiotic *Rhizobia*-legume relationship.

1. Rhizobia. Biological nitrogen fixation via Rhizobia are estimated to supply 12.7 million tons annually to world crops (Frissel, 1978), about 10% of the total annual N supply (Table 3). Hardy and Havelka (1975) speculatively estimated that *Rhizobium*-legume symbiosis contributes 80 million tons of N annually to agricultural soils, being split approximately equally between crops and pastures. Other estimates (NAS, 1977b) are for 35 million tons of N being fixed by agricultural legume crops. The authors of this report feel that the data quoted by Frissel are more realistic, especially when crop legume N uptake, yields and hectarage are considered. Legume (soybeans, peanuts, pulses) uptake of N is estimated to be 88 kg/ton yield. In 1979, 165 million tons of legume grain were produced on 148 million hectares (FAO, 1980a). Multiplying 88 kg N/ton legume yield by 165 million tons, one obtains the figure of 14.5 million tons of N taken up by grain legumes in 1979. This is closer to Frissel's 12.7 million tons than the other reported estimates. The world's 3150 million hectares of pastures are also benefited by symbiotic N fixation; the only estimate of quantities of N rhizobially fixed with pastures is the 40 million tons of N speculated by Hardy and Havelka (1975).

2. Associative symbioses. Associative symbiosis between grasses and bacteria has intrigued scientists since postulated by Parker (1957) and observed by Dobereiner (1961, 1966). Though inconclusive works with *Azospirillum brasilense* and roots of tropical grasses and maize indicate possibilities for microbes supplying some N to tropical grasses (Marx, 1977), more recently, a review of the literature by Weier (1980) noted specific associations of *Paspalum notatum*-*Azotobacter paspali*, *Digitaria decumbens*-*Azospirillum brasilense* and sugar cane - *Beijerinckia indica* to fix up to 100 kg N/ha/yr. Weier and MacRae (1981) have found in northern Australia native and introduced grasses when associated with N-fixing bacteria to fix up 126 kg N/ha/yr. When Schank et al., (1981) inoculated *Digitaria* sp. with *Azospirillum brasilense*, dry matter yields increased over control by 23% on a low N podzol and 8.5% on a high N Vertisol. Clearly, possibilities exist for increased N supply to tropical grasses through this associative symbiotic relationship, though considerably more research is needed.

3. Azolla culture and blue-green algae. The *Anabaena*-*Azolla* symbiosis offers a source of organic N fertilization as green manure under flooded conditions, and thus is of particular interest to paddy rice cultivation and of some potential magnitude in the world's cereal grain-N situation. Projections by FAO (1978) are that *Azolla* cultivation in the developing world could produce 1.5 million tons N per year for rice. Much research with *Azolla* is inconclusive, although indications are that it can fix as much as 800 kg N/ha/yr (Gunasena et al., 1979). The Chinese have reported paddy rice yield increases with *Azolla* ranging from 0.4-158%, with an average of 19% over 422 field experiments (Lumpkin and Plucknett, 1980). Blue-green algae and green manures other than *Azolla* are also possibilities.

D. Organic Fertilizers

Approximately 6% of the primary nutrients supplied to the world's 1414 million hectares of cultivated and permanent crops is estimated to come from organic manures (Table 3) as dung, because no data are available about crop residues remaining on harvested cropland. FAO (1975) estimated that nearly 10% of all applied fertilizers were composed of organic manures and that there is potential to increase this to about 25%. The total amounts of fertilizer N, P_2O_5, K_2O in organic manures worldwide in 1971 was estimated by the World Bank (1979) to have been 48, 16 and 39 million tons, respectively with cattle manure accounting for 1/3 of each nutrient. This total amount of 103 million tons of nutrients in organic waste was nearly fourfold greater than the total consumption of these nutrients from inorganic fertilizers (28.6 million tons) in the developing countries in 1978/79. However, the estimates in Table 3 show that only 17 million tons of these primary nutrients were actually applied to the world's arable and permanent cropland.

China and India are the two main countries utilizing organic wastes as fertilizers. Interesting data were presented by Kemmler (1979) showing that while the 13.4 kg grain production/kg N, P_2O_5, K_2O applied in China by a combination of organic and inorganic fertilizers is almost as high as that in Japan; the levels of N, P_2O_5, K_2O consumption/ha and of cereal yields are nearly three times higher in Japan.

There may be possibilities for increasing the recycling of organic wastes as manures to crops. However, many factors such as competitive uses for fuel, bulk, low nutrient contents, loss during collection, storage and economics lessen the potential benefit of organic nutritional sources for food production. Still, even small increases in the proportion of nutrients recycled could result in appreciable food production increases (NAS, 1977c).

E. Increasing the Efficiency of Input Use

The supply-demand pictures show a major urgency in increasing the total fertilizer production capacity in the developing countries at an unprecedented scale as well as major efforts in additional plant nutrients from biological and organic sources. That statement, however, must be brought into the context of limited energy supplies for production and distribution of nutrient inputs.

Pimentel (1979) stated that the world's energy resources are too limited to feed even our present population utilizing the highly energy consuming U.S. food production system. In fact, if petroleum were the only source of energy for food production and if all petroleum reserves were used via the U.S. high energy consuming system to produce food for the world's population, the 87 trillion liters of fuel reserves would last only 13 years (Pimentel, 1979). Though his estimates may be questionable, Pimentel makes a point--that fertilizer production systems utilizing either less energy or making more efficient use of inputs must be developed, especially for developing countries.

There are several ways to increase the efficiency of input use and these are not mutually exclusive. One is certainly that major efforts are needed to produce plant nutrients more efficiently. The classic western style models of large fertilizer plants may be considered one extreme, with the "backyard" ammonium carbonate factories of China's communes as the other. In between there are myriads of alternatives which could permit locating the developing countries' production of fertilizer plants closer to both the sources of nutrient supply and the centers of food production, thereby reducing energy costs in terms of both production and transportation.

Another would be looking at traditional and non-traditional agronomic approaches. Improved methods of placement and time of application of fertilizer nutrients (Fagi and DeDatta, 1981) will certainly play a large role in increased efficiencies of these nutrients, be they from inorganic or organic sources. The increased N efficiencies in rice production in Asia by deep placement of urea supergranules is one such example (Yamada *et al.*, 1979).

Another way of utilizing plant nutrients more efficiently would be the use of germplasm tolerant to suboptimal soil conditions. Evaluation and selection of crop species and varieties tolerant to suboptimal soil and climatic conditions, especially Al and drought tolerances, has been widely acknowledged as a major research area (NAS, 1977b; NCSU, 1979; IRRI, 1980). Evaluation and selection of crops and varieties tolerant to acid soils could be of major benefit in opening up many areas of the humid tropics and seasonal savannas where these soils predominate. Evaluation and selection of salt tolerant plants could do the same for saline soils in the arid and semiarid regions of the world (FAO, 1980b). Research possibilities of tolerance to adverse soil conditions are not limited just to plant germplasm, as tolerances among Rhizobial strains are also varied (App et al., 1980). Therefore, the "green revolution" may become the "adaptive revolution" in which soil scientists, plant breeders and microbiologists work together to evaluate, select and develop crop cultivars and beneficial soil microbes which are capable of producing food on less than optimal soil conditions, at lower fertilizer inputs than with varieties produced by the "green revolution."

Another possibility is improved utilization of mycorrhizae, expediters of nutrient absorption, particularly P, by plant roots. Ectotrophic mycorrhizae have long been known to be important to trees. Endotrophic mycorrhizae recently have been found to almost ubiquitous and to infect crops (NAS, 1977b). Mycorrhizae help supply the most infected plants with enlarged root systems, thereby improving the absorption of P, Mg, Ca, some trace elements, and water, and in legumes stimulating N fixation, and improving overall growth of both non-legumes and legumes due to better mineral nutrition. Their activities are especially beneficial to tropical legumes and thus could be of importance in establishing legumes on acid soils (NAS, 1977b). Safir (1980) has summarized field work which has shown corn and wheat yield improvement with use of heavily mycorrhizal seedlings and soybean yield increases following inoculation with mycorrhizae.

Thus, increasing the efficiencies of input use as related to plant nutrition can be addressed in many potential ways. Looking at the overall situation,however, one is impressed by the fact that increased efficiency of plant nutrients depends to a large extent on soil constraints.

F. Dependency on Soil Constraints

Plant nutrition under field conditions is far from a simple matter of supplying nutrient inputs and producing crop outputs. In addition to the many interactions that take place among nutrient sources, several other factors exert major influences on plant nutrient efficiency. Adverse soil conditions such as high acidity, salinity or drought can easily decrease plant nutrient utilization to very low levels. Physical soil constraints such as erosion, surface crusting and others can have a similar impact. It is difficult, therefore, to view plant nutrition research solely in the context of soil fertility, i.e., the capacity of the soil to provide nutrients for optimum plant growth. One immediately asks, what soil? Which farming systems? It seems more practical to consider the broader issue in terms of soil management, i.e., the manipulation of soil properties and inputs to increase production on an agronomically, economically and ecologically-sound basis.

Scientists and administrators of research programs in developing countries are increasingly aware of the importance of soil-related constraints as the next major bottleneck in tropical agricultural research. Earlier production breakthroughs came with high yielding varieties on fertile soils with adequate irrigation systems. The limits of direct adaptability of such technology are largely being reached. The genetic breakthroughs and accompanying cultural practices are insufficient in the face of environmental constraints of which soil and water are the main ones. Consequently, the authors of this report decided to consider within the scope of this study the soil constraints that affect plant nutrition under field conditions in developing countries.

IV. MAJOR WORLDWIDE ASSESSMENTS

The increasing awareness of the importance of plant nutrition on world food production has stimulated a series of studies on research priorities related to plant nutrition. Seven major studies were conducted during the last six years, where working scientists met and developed a list of priorities in response to requests from different sponsoring institutions. Many other conferences have dealt with this subject during the last six years but the authors of this study are not aware of other studies that led to detailed research priorities formulated by scientists actively engaged in plant nutrition research for the developing world. A short description of the seven studies follows in chronological order. Table 6 summarizes the outcome of these studies under a common format. The term "research component" is used herewith to underscore the interdependence of these issues, as mentioned in all studies.

A. Crop Productivity: Research Imperatives (October 1975)

This study focused on identifying the fundamental biological processes that control the productivity of economically important food crops and/or the utilization of non-renewable resources. It was sponsored by Michigan State University, the Charles F. Kettering Foundation with the support of the U.S. National Science Foundation, the Energy Research and Development Administration, the U.S. Department of Agriculture and USAID. A total of 96 scientists, mostly U.S.-based, participated in the working sessions that dealt specifically with plant nutrition (nitrogen input; water, soil and mineral input; and environmental stress). A total of 20 priority research components are identified in Table 6 under the heading "M-K 1975." The proceedings are published in a book edited by Brown et al., 1975).

B. Cornell-National Science Foundation (1976)

A study entitled "Potential Increases in Food Supply Through Research in Agriculture" was conducted by Cornell University with the participation of 16 scientists, mostly U.S.-based. Two volumes relevant to plant nutrition were produced, "Fertilizers and Increased Food Production" (Lathwell, 1975) and "Researchable Areas Which Have the Potential for Increasing Crop Production" (Ozbun,1976). A total of 14 priority research components were identified. They are shown in Table 6 under the heading "Cornell 1976."

C. FAO: Improved Use of Plant Nutrients (1977)

FAO held an expert consultation in April 1977 to review plant nutrition research and develop a set of recommendations. A total of 34 scientists from different parts of the world participated. Fifteen research priorities are reported in Table 6 under "FAO 1977." A published report is available (FAO, 1978b).

D. National Academy of Sciences: World Food and Nutrition Study (1977)

A worldwide assessment of food and nutrition was produced by the National Academy of Sciences in response to a request from the President of the United States, arising from the World Food Conference. Working groups on crop protivity and resources for agriculture identified priorities relevant to plant nutrition. A total of 26 scientists participated in the development of priority profiles relevant to this study. The overall recommendations and the detailed reports of these two work groups are available as separate volumes (NAS 1977abc). A total of 21 priority research components related to plant nutrition are identified in Table 6 under the heading "NAS 1977."

E. Soil Constraints Conference (1979)

This conference was co-sponsored by IRRI and Cornell University and was held in Los Baños in June 1979 with support from USAID and the German Agency for Technical Cooperation (GTZ). The specific purpose was to develop priorities for alleviating soil-related constraints to food production in the tropics. It was a joint effort of 75 scientists from developing and developed countries as well as from the international centers. The proceedings have been published by IRRI (1980). Two follow-up meetings of a steering committee set to pursue implementation of the priorities have been held. Twenty-five research components are identified in Table 6 under the heading "SCC 1979." These priorities were arranged according to three major agroecological zones.

F. North Carolina State University: Soil Management Collaborative Research Program (1979)

This USAID-sponsored study aimed at identifying priorities for the Soil Management Title XII Program. A total of 197 scientists and administrators from 46 countries representing 118 different institutions provided inputs. Priorities were developed with the assistance of an External Advisory Panel of international soil scientists. Extensive travel to developing countries was conducted as a major part of the study. A report is available (NCSU 1979). Twenty-seven research components are shown in Table 8 under "NCSU 1979," arranged into five major agroecological zones in the report.

G. Bonn Conference on Agricultural Production (1979)

The most recent study was organized and sponsored by the GTZ, the German Foundation for International Development (DSE), the Federal Ministry of Economic Cooperation (BMZ) and the Rockefeller Foundation. The objective was to assess research and development strategies for increasing agricultural production in the 1980's and beyond. A total of 63 scientists developed priorities relevant to plant nutrition in the panel on soils, energy, water and biological resources (Wolff, 1979). Background reports prepared prior to the conference are also published (Bentley et al., 1979; Hanson, 1979; Leach, 1979; Levine et al., 1979). The unpublished draft report of the soils panel (Bentley 1979) describes a framework of research components by agroecological zones and a set of assessment parameters. A total of 24 priority research components were arranged in terms of five agroecological zones and are shown in Table 6 under "Bonn 1979."

Table 6. Summary of priority research and development components identified by the seven assessment studies conducted between 1975 and 1979.

Research and Development	Priority Assessment Studies* M-K 1975	Cornell 1976	NAS 1977	FAO 1977	SCC 1979	NCSU 1979	Bonn 1979
A. RESOURCE APPRAISAL							
1. Soil characterization and classification	X				X	X	X
2. Soil classification for plant nutrition			X	X	X	X	X
3. Soil fertility evaluation		X		X	X	X	X
4. Fertilizer supplies, price, distribution and use			X				
5. Fertilizer manufacturing technology	X		X				
B. STRESS FACTORS							
1. Selection of germplasm tolerant to soil stresses	X	X	X	X	X	X	X
2. Management of soil acidity	X	X	X	X	X	X	X
3. Salinity	X	X	X	X	X	X	X
C. NUTRITIONAL CONSTRAINTS							
1. Nitrogen fertilizer efficiency	X	X	X	X	X	X	X
2. Phosphorus fertilizer management		X	X		X	X	X
3. Potassium and nutrient balance			X		X	X	X
4. Sulfur			X	X	X	X	X
5. Micronutrients			X	X	X	X	X
D. BIOLOGICAL CONSTRAINTS							
1. Biological nitrogen fixation	X	X	X	X	X	X	X
2. Organic residue utilization	X	X	X	X	X	X	X
3. Photosynthetic efficiency	X	X	X				
4. Rhizosphere effects	X		X		X	X	X
5. Basic stress physiology and genetics	X						

Table 6 (continued).

Research and Development	M-K 1975	Cornell 1976	NAS 1977	FAO 1977	SCC 1979	NCSU 1979	Bonn 1979
	Priority Assessment Studies*						
E. PHYSICAL SOIL CONSTRAINTS							
1. Water management in rainfed systems	X		X		X	X	X
2. Erosion prevention and control	X			X	X	X	X
3. Mechanical impedance	X				X	X	X
4. Land clearing methods					X	X	
F. IMPROVED FARMING SYSTEMS							
1. Sustained production in Oxisols/Ultisols	X		X		X	X	X
2. Multiple cropping	X	X	X	X	X	X	X
3. Agroforestry					X	X	X
4. Intensive fertilization of high value crops		X					
5. Management of irrigated farming systems in arid areas	X		X			X	X
6. Low fertilizer input farming systems	X				X	X	X
G. TECHNOLOGY TRANSFER							
1. Validation and adaptation of research results	X	X	X	X	X	X	X
2. Training	X	X	X	X	X	X	X
3. Developing fertilizer recommendations		X		X		X	
4. Information Services					X	X	

*For identification see text.

V. RESEARCH AND DEVELOPMENT NEEDS

Assembling Table 6 required some necessary interpretation by the writers of this report, as the specific objectives and terminology of the varied. The participation of one or both writers of this report in the last four studies, including related travel, facilitated this task. For more detailed information, the readers may wish to consult the publications of the specific assessment reports (Brown et al., 1975; Lathwell,1975; Ozbun,1976; National Academy of Sciences,1977abc: FAO,1978b; NCSU,1979; Wolff,1979; Bentley et al., 1979; Hanson,1979; Leach,1979; Levine et al., 1979; IRRI, 1980).

Table 6 shows considerable agreement as to what are the priority research components related to plant nutrition. The aggregate total of 32 components arising out of seven separate studies that identify an average of 21 priorities each is remarkably low. It seems appropriate to consider this list as a consensus of research priorities arising from the opinions of over 300 scientists from more than 50 countries representing more than 150 different institutions around the world.

No weighting is given or implied in the ordering of these research components. They are arranged in broad categories: Resource appraisal, overcoming stress factors, mineral nutrition aspects *per se*, biological aspects, physical aspects, farming systems and technology transfer aspects, in an attempt to group them in a logical but not totally satisfying fashion. It should be emphasized again that the three most recent studies arranged these research components by agroecological zones, recognizing that priorities differ in different major regions of the developing world, although many cut across geographical regions. The relative weighting by agroecological zone will be treated in a subsequent chapter.

A. Research Components Related to Resource Appraisal

All studies have emphasized the need for a better characterization of the land resource base as a prerequisite for tackling plant nutrition problems in the field. Without knowing to a reasonable degree what the soil resources are, it is difficult to develop or transfer technology that would improve plant nutrient utilization. The three 1979 studies recognize three research components that, operating in sequence, carry the assessments of a geographical area to individual farmer fields: 1) Soil survey and classification; 2) interpretation of classification terminology in terms of soil-related constraints; and 3) soil fertility evaluation at the farmer's fields. From the chemical input side, the status of fertilizer production, supply and marketing, plus the development of improved fertilizer manufacturing technology have been identified as priority research components.

1. Soil characterization and classification. Although a soil map of the world has been produced by FAO at the scale of 1:5 million, much of the data base from developing countries consists of general estimates or exploratory studies (FAO-UNESCO, 1971-1979). More systematic studies are needed in developing areas in order to provide a reasonable assessment of attributes

and limitations of the soils. The degree of detail or the methodology used varies with the intended use. Research on how to characterize and classify soils is not considered high priority. The gap consists of the limited geographical coverage at sufficient detail. It is an operational issue, and thus a development component. Whenever possible, land classification rather than soil classification is more appropriate as it includes also climate, present vegetation and sometimes available infrastructure. Examples of regional studies are CIAT's land resource evaluation of tropical Latin America (Cochrane et al., 1979) and FAO's agroecological zones project (FAO, 1978a). The degree of importance of this component varies very much with countries and regions although most developing countries have begun more detailed systematic soil inventories in relation to present and potential land use. Such studies will yield much basic information and require continuing support.

Given the diverse methods of analyzing and classifying soils, it has been difficult in the past to transfer basic soil information from one country to another in a way that is readily understood. Within the last decade major advances have been made in the development of quantitative classification systems such as Soil Taxonomy (SCS, 1975) that are based on criteria determined by specified methodologies. The expanded use of quantitative soil classification provides a common language akin to plant taxonomy. Expanding the use of quantitative classification systems throughout the developing world is considered a high priority activity (Swindale, 1978; IRRI, 1980). Research on how to improve these systems for better adaptability to tropical areas is in progress by a series of international work groups and should continue.

2. Interpretation of soil classification into plant nutrition constraints. Soil classification systems are essentially ways to store morphological, chemical and physical data in a systematic and retrievable fashion. Soil taxa do not directly identify plant nutrition constraints. Furthermore, classification systems concentrate on the more stable subsoil properties rather than on the highly dynamic topsoil properties. This divergence has resulted in a major communication gap between the soil classification specialists and agronomists who are primarily interested in topsoil properties because they most directly affect plant growth. Quantitative classification systems therefore, need to be translated or interpreted into technical systems for plant nutrition purposes. One such attempt is the Fertility Capability Classification System (FCC) which selected out of Soil Taxonomy and topsoil properties a series of parameters that can be routinely analyzed to identify constraints to plant nutrition in a quantitative fashion (Buol et al., 1975; Buol and Nicholaides, 1980). Another approach is to develop ways of transferring fertility management information from thoroughly classified soils to other soils classified at the same family level (Benchmark Soils Project, 1979). Latest advances in this project indicate that transferability is significantly increased when soil test data not included in Soil Taxonomy are incorporated in the analysis (Cady and Silva, 1980). FAO's Framework on Land Evaluation also includes "ability to supply nutrients" as one of its land qualities (FAO, 1976). Significant interaction among these three approaches is taking place. The World Food and Nutrition, Soil Constraints, North Carolina and Bonn studies strongly recommended strengthening research on technical interpretations of soil classification systems for plant nutrition purposes and their adaptation to specific farming systems by national programs.

3. Soil fertility evaluation. The third step in the process of appraising soil resources for plant nutrition purposes is soil fertility evaluation, often incorrectly referred to as soil testing. Soil fertility evaluation is the process by which plant nutrition constraints of individual farm fields are identified and fertilizer recommendations are made. Several approaches are in use throughout the world, but the most widespread are based on soil testing, plant analysis, missing element techniques, fertilizer response trials and frequently a combination of these (Sanchez, 1976). A major review of soil and plant testing as a basis for fertilizer recommendations has been prepared by Cottenie (1978). In most developed countries, soil fertility evaluation services are well developed and constitute one of the foundations of successful agriculture as well as one of the most important means of increasing the efficiency of fertilizer use. In developing countries, one of the most successful programs has been the International Soil Fertility Evaluation and Improvement Program (ISFEIP) which developed simple, low cost procedures and established a network of national soil fertility evaluation services in most countries of Latin America (ISFEIP, 1974; Palencia et al., 1975; Hunter, 1975; Waugh et al., 1975). That program terminated in 1975. In tropical Asia, only India has a major national program. Lack of adequate methods for formulation fertilizer recommendations for flooded rice is a major limiting factor in this region, and it even hampers the development of soil fertility evaluation services for upland crops in Southeast Asia. In much of Africa the very limited research conducted at adequate rates of fertilization, coupled with the unavailability or very high costs of fertilizers have largely prevented the establishment of workable soil fertility evaluation services, except on certain large scale plantations. The FAO fertilizer program has provided an impressive amount of field fertilizer response data, which is now available in computerized form by country.

The need to initiate or strengthen soil fertility evaluation services was the most widely mentioned research need by developing country scientists in the NCSU study. The Cornell, FAO, Soil Constraints and Bonn studies have also endorsed the high priority nature of this component. The need for determining the critical levels of plant nutrients of new varieties that are rapidly being developed is a clear prerequisite for improving plant nutrition at the farmers' fields. With the exception of N for which no adequate rapid diagnostic technology is available, the efficiency of utilization of plant nutrients largely depends on the effectiveness of soil fertility evaluation services.

The research and development needs vary with the level of development in different countries. Lopes and Sanchez (1980) have listed specific activities for regions or countries with 1) only rudimentary soil fertility evaluation services, 2) operational semiautomated laboratories, calibration and correlation at the greenhouse level, and 3) those with adequate operational facilities and field testing.

4. Fertilizer supplies, price, distribution and use. Turning to the input site of plant nutrition, the research and development priorities focus on fertilizers. The World Food and Nutrition Study recognized that some of the main constraints to increased fertilizer use in developing countries lie in the limited understanding that planners have about 1) the economic and

social factors that persuade farmers to increase food production through increased fertilizer use and 2) the factors that govern fertilizer supplies (NAS, 1977c). This results in cyclic imbalances with major detrimental consequences on food production. The NAS study identified five areas of research to alleviate this constraint:

a) Establish a better understanding of the economic and social factors that influence the farmers' use of fertilizers. This includes the inclusion of risk factors in fertilizer response studies.

b) Develop improved methods of demand analysis and forecasting of fertilizer use.

c) Develop a methodology for reliable fertilizer supply forecasts.

d) Develop a system that will collect and transmit reliable information cheaply to central points.

e) Develop investment analysis tools for policymakers.

Since then, country studies made by IFDC have significantly contributed to this direction and such efforts should continue.

5. Fertilizer manufacturing technology. The Michigan-Kettering and National Academy of Sciences studies identified lowering the cost of fertilizer manufacturing as an important research priority in view of the energy limitations of most developing countries and the world as a whole. The main aspects of this research priority identified by NAS (1977c) are:

a) Improve ammonia production through coal gasification.

b) Develop alternate sources of hydrogen for ammonia production, such as low cost water hydrolysis, thermochemical processes, photoinduced electron transfer processes and the use of waste hydrocarbons.

c) Develop an abiological process of fixing nitrogen without using hydrogen.

d) Assess accurately the size, quality and economic potential of global reserves of phosphate rock.

d) Develop new or improved methods for the mining and beneficiation of phosphate ores of generally different composition from those found in developed countries, for example, those having high contents of silica, carbonate, iron, aluminum or chlorides.

f) Develop improved acidulation technology designed to handle inferior grades of raw materials.

g) Develop improved diagnostic techniques to determine the suitability of direct application of phosphate rock to the soil.

Other aspects identified since by IFDC (1980) also merit mention:

h) Transform prilled urea plants to produce granules of differing size through pan granulation. Granular urea improves physical properties and permits the use of large sizes with slow release properties for rice culture (IFDC, 1980).

i) Assess the potential use of lower cost clinker process of phosphate rock acidulation which appears promising for relatively remote areas such as the Sahel where small scale plants can satisfy the relatively low but important demand for P.

B. Research Components for Alleviating Stress Factors

The second major group of research components include those related to alleviating widespread soil constraints such as soil acidity, low available soil phosphorus levels, salinity and drought. In the past, the conventional approach has been to eradicate such constraints by sufficient liming, superphosphate applications, drainage and irrigation. In other words, alter the soil to fit the plant's nutritional demands, thereby eliminating or reducing stress factors. In response to the energy crisis, a different approach has been developed based on the concept of using plants that tolerate to a significant degree these soil constraints; in other words, fit the plants to the soil's limitations (Foy and Brown, 1964; Spain et al., 1975). These efforts have caused misconceptions such as the belief that "fertilizer-proof" varieties can be developed and that such tolerant plants could "mine the soil of its available nutrients." A recent review on this subject as applied to acid soils shows that the more successful research results are based on the use of tolerant germplasm together with lower rates of fertilizers and lime. This combination produces reasonably high but seldom maximum yields, but has the advantage of approaching the highest yield per unit of plant nutrient input (Sanchez and Salinas, 1981). Three main research components fall into this category: Select tolerant germplasm, manage acid soil stresses and manage saline soils. It is relevant to note that the first two research components are mentioned prominently in the seven assessment studies (Table 6).

1. Selection of germplasm tolerant to soil stresses. Research conducted within the last ten years has demonstrated that plant species and varieties differ significantly in their tolerance to excess amounts of available Al, Mn, Fe, B, high electrical conductivity, high organic acid levels as well as to low levels of available P, Ca, Mg, Fe, Zn, Cu and other plant nutrients. The literature has been compiled in several recent reviews (Wright, 1976; Ponnamperuma, 1977; Jung, 1978; Andrew and Kamprath, 1978; Mussell and Staples, 1979; Sanchez and Salinas, 1981). They provide ample evidence that many of these differences are agronomically relevant and many of them are controlled by rather simple gene combinations that allow breeding for tolerance to specific stresses.

Acid, inherently infertile soils, mostly classified as Oxisols and Ultisols cover approximately 43% of the tropics. Acid soil infertility is often due to the combination of individual stress factors, principally Al toxicity, deficiencies of P, Ca and Mg, and to a lesser extent, Mn toxicity. These stresses interact with each other. Several plant species and varieties are tolerant to two stress factors, such as Al toxicity and low P availability. Selection and breeding efforts have identified several important species of annual food crops, pastures, perennial crops and trees that are generally quite tolerant to acid soil stresses. Sanchez and Salinas (1981) report 51 such species, including cassava, cowpea, upland rice, pigeon pea, coffee, mango, oil palm, rubber, Andropogon gayanus and Stylosanthes guianensis. In addition, acid-tolerant varieties of generally sensitive species such as wheat, soybeans, maize and sorghum have been identified. The use of acid-tolerant varieties and species decreases the liming requirements often to low rates sufficient to serve as Ca and Mg fertilization. In addition, Al tolerant plants are able to penetrate acid subsoil layers, thereby being able to tap a larger volume of soil and utilize available water in the subsoil. Aluminum tolerant varieties or species therefore, contribute significantly to better soil moisture utilization and enable plants to withstand drought stress periods. In the case of legumes, Al tolerance of the rhizobium is as important as Al tolerance of the plant. Fortunately rhizobium strains also differ in their ability to tolerate acid soil stresses (Munns, 1978; Date and Halliday, 1979).

Tolerance to the various factors involved in soil salinity (high electrical conductivity, high Na saturation) has also been studied, up to the point of identifying tomato varieties capable of growing in dilute salt water (Epstein, 1976). The widespread use of such germplasm would reduce, but not eliminate the need for drainage and gypsum for alleviating salinity and alkalinity constraints.

Varietal differences of rice in tolerating several stress factors found in flooded soils have been identified by Ponnamperuma (1977). The main stresses are Fe and B toxicity, Zn, Fe and P deficiency, and high organic acid concentrations. Breeding for multiple stress tolerance has been recommended as a way to better fit rice varieties to specific marginal soils (F. N. Ponnamperuma, personal communication).

The evidence suggests that joint efforts between soil scientists, plant breeders and microbiologists be expanded in order to identify germplasm tolerant to adverse soil conditions throughout the developing world. The main avenues include:

a) Characterization of main varieties or ecotypes of the relevant species for an area for their tolerance to adverse soil factors in quantitative terms. Determine the critical levels for each factor beyond which yields substantially decrease.

b) Match these plant critical levels with soil critical levels for deficiencies or toxicities as identified by soil fertility evaluation.

c) Collect germplasm (plant and rhizobia) and screen them for tolerance to adverse soil factors.

d) Breed for single or multiple soil stress tolerances and combine with other desirable agronomic attributes such as yield potential and seed quality.

Breeding for tolerance to soil stresses is in its infancy in comparison with breeding for insect and disease resistance. Special techniques may have to be developed. Nevertheless, breeding for soil stress tolerance has the advantage that the adverse soil factors do not mutate as pathogens often do.

2. Management of soil acidity. Soil acidity is a major barrier preventing the development of large areas of the humid tropics and acid savanna regions of the world where much of the expected increased in cultivated land is likely to occur. In tropical America, for example, there are over 700 million hectares affected by Al toxicity, Ca and Mg deficiencies (Sanchez and Cochrane, 1980). An additional 400 million has of soils with the same constraints are found in Africa and in 236 million hectares of Southeast Asia (W. Couto and P. A. Sanchez, unpublished). Although topsoil acidity can be eliminated by liming to pH 5.5 in order to neutralize the exchangeable Al, several economic constraints limit this straightforward solution to a small proportion of the acid soils. The seven assessment studies concur that research efforts should be aimed at developing a package of practices designed to alleviate this major constraint. According to Sanchez and Salinas (1981) the following aspects should be considered:

a) Identify plant species and varieties tolerant to Al and Mn toxicities.

b) Apply enough lime to satisfy plant Ca and Mg requirements and to decrease Al saturation levels below those that plants cannot tolerate.

c) Promote the downward movement of Ca and Mg into the subsoil in order to increase root development.

d) Develop practices that prolong the residual effect of liming.

e) Prevent the development of secondary acidity. Secondary acidity is that caused by the residual acidity of added fertilizers, particularly N sources, in soils with low buffering capacity.

Secondary acidity is not only important in acid soils that have been limed, but also in non-acid soils such as those of the semiarid tropics of Africa (IRRI, 1980).

Other important constraints also arise when lime use is introduced in new areas. The lime deposits need to be identified and characterized. Crushing equipment for producing a fine grade of calcitic or dolomitic limestone in the carbonate form is needed. The only source available in some areas is slaked lime, $Ca(OH)_2$, which is needed for building and road construction. $Ca(OH)_2$ is a poor liming material because of physical problems, and short residual effects. Although no new technology needs to be developed, attention should be given to the composition, chemical form and fineness of limestone production and its transportation to the users.

Financing agencies should look at lime and basal phosphate applications as capital improvements and not as inputs to get the first planting underway. The residual effect of appropriate lime applications should last for several years. The use of these amendments, therefore, should be amortized over the period of time they are expected to be effective.

3. Salinity. Three major types of salinity can be distinguished, saline soils in arid areas under irrigation, secondary salinity, and coastal saline soils. Technology for ameliorating saline soils through irrigation, drainage and gypsum applications is one of the most advanced and quantified aspects of soil science (Soil Salinity Laboratory, 1954). Nevertheless, the application of such knowledge in many irrigation projects in the developing world is often clearly inadequate. Technology transfer, with emphasis on training water management specialists is urgently needed in many irrigated areas of the Middle East and South Asia. There are, however, two researchable issues: 1) The relative tolerance of new species and cultivars to salinity, 2) the use of green manures to ameliorate sodic soils (Bentley, 1979).

Secondary salinity is that caused by mismanagement of irrigation water, transforming non-saline soils into saline ones. This problem is very prevalent in the areas previously mentioned and also in small irrigation systems found in the semiarid tropics (IRRI, 1980).

Much less is known about coastal saline regions, many of which could be devoted to rice production in Asia. The Soil Constraints Study (IRRI, 1980) suggested the following research topics:

a) Demarcate the different kinds of salt-affected soils in wetland regions.

b) Determine their soil dynamics and the variability of their chemical, physical, hydrologic and climatic properties.

c) Establish the critical levels for salinity tolerance for important food crops, and breed varieties for salinity tolerance.

d) Develop criteria for determining which saline lands have potential for rice or other crops and what the cost/benefit ratios of development would be.

C. Research Components for Alleviating Nutritional Constraints

The third group of priority research components comprise those that are directly related to the availability and efficiency of plant nutrient elements. Among the essential nutrient elements, the assessment studies assigned priority attention to N, P, K, S and micronutrients in general. Also, four studies called attention to the issue of nutrient balance, particularly between K, Mg and Ca.

1. Nitrogen fertilizer efficiency. This research component was not only considered in all seven studies but was given high rankings in all of them. Lack of sufficient N is the most widespread plant nutrient deficiency in terms of land area of any nutrient in the tropics (Sanchez, 1976). Nitrogen is also the most expensive and energy requiring of fertilizer sources and the most widely used. Unlike P and K, N fertilizer needs are difficult to predict quantitatively because the dynamics of inorganic N limits the use of soil analysis. Agronomic experience based on field fertilizer trials is usually the best guide. Usually less than half the N applied as fertilizer is recovered by most annual crops. Recovery is substantially lower in poorly managed flooded rice systems where alternating oxidation-reduction accentuate loss mechanisms. Not all the unrecovered N is lost because some may enter the organic pools and be subsequently released to plants. Nevertheless, losses through leaching, volatilization and denitrification are of major proportions. Furthermore, inorganic N tends to surpress biological N fixation in the soil and in nodules of legume roots, thus decreasing the efficiency of the sources of N. Organic nitrogen additions as manures, crop residues, and compost also affect the efficiency of applied N, but relatively little is known about the interactions between these sources of N.

The main areas requiring attention are summarized below, many of which are drawn from the review by Bouldin et al., (1980) and the conclusions of the various assessment studies. These research issues are not relevant to legume plants or to grass/legume associations where no N fertilization is contemplated.

a) Although the basic concepts of N management are well known for most cropping systems, site-specific fine tuning is needed. It is suggested that N management research follow an integrated approach considering that plant N uptake at a desired yield level is a function of N mineralized from soil organic matter, N mineralized from organic additions (crop residues, legume residues and manures), biological N fixation and fertilizer N.

b) An exception to the above statement is the need to understand the basic concepts of N management in intercropped systems, and in several tropical crops that have not been thoroughly studied.

c) Maximize the recycling of N through use of crop residues, rotations or interplantings with legumes, and utilization of organic N. Bouldin et al., (1980) described the Chinese experience where 2/3 of the N comes from organic sources, and the possible adaptations and limitations to other areas.

d) Quantify loss mechanisms better, particularly leaching in well drained soils, and denitrification and ammonia volatilization in wetlands.

e) Evaluate new N sources and methods of application. An important breakthrough appears to be in the making with the deep placement of urea supergranules in flooded rice soils. Work by IFDC and IRRI indicate that the N efficiency of flooded systems without ideal water control can increase from about 25 to 60% (IFDC, 1980). Similar efforts that evaluate combinations of nitrogen sources, placement and timing of application should be encouraged throughout the developing world.

f) Develop a practical test for estimating available soil N.

2. Phosphorus fertilizer management. Phosphorus deficiency is a widespread problem throughout the tropics, particularly in the humid tropics where the dominant soils are Oxisols and Ultisols, in Vertisols of the semiarid tropics and in Andisols derived from volcanic ash. In addition, most Oxisols, Ultisols and Andisols with loamy or clayey topsoil texture fix large quantities of added P, thereby rendering that nutrient at best only slowly available for plant growth. There are about 1100 million hectares of soils with high P fixation capacity in the developing world (W. Couto and P. A. Sanchez, unpublished data). The residual effects of P fertilization in high-fixing soils however, can last for many years. For example, an application of 1280 kg P_2O_5/ha as triple superphosphate broadcast and incorporated into an Oxisol of Brazil has produced an average of 6.3 tons/ha of corn per crop during the past nine years. Economic analysis assuming a 25% annual interest rate on capital and price:cost ratio of 6.7 kg corn to pay for 1 kg of P_2O_5 showed that this alternative was more profitable than small yearly applications (Yost et al., 1979; Sanchez, 1981). As in the case of lime, basal or corrective phosphorus applications should be viewed as a capital investment and financed accordingly.

In many cases, socioeconomic constraints prevent the application of large quantities of P to high fixing soils. For soils that are both deficient in P and have a high fixation capacity, a phosphorus fertilizer management strategy needs to be devised for major farming systems. The main research components to develop such a strategy are:

a) Evaluate different sources of P, in order to determine the feasibility of direct application of phosphate rocks.

b) Determine better placement methods, including combinations of banded and broadcast applications.

c) Conduct long-term studies on the residual effect of phosphorus applications to evaluate their full economic value.

d) Determine the critical requirements of P by main varieties and plant species both in terms of external (soil) and internal (plant) requirements.

e) Select plants that utilize more efficiently low levels of available soil phosphorus.

f) Determine the role and potential of endomycorrhizal inoculations for increasing the ability of plants to absorb phosphorus from the soil.

g) Elucidation of the interactions between soil amendments and phosphate applications as well as P-organic matter interactions.

3. Potassium and nutrient balance. According to interpretations based on the FAO World Soils Map, approximately 27% of the developing world's land is dominated by soils with low K reserves (W. Couto and P. A. Sanchez, unpublished). With continuous cultivation and crop intensification, particularly if N and P fertilizers are used, the rate of K release in soils with low reserves decreases below the critical level and K fertilization is needed (Kemmler, 1980). Although the chemistry of K in soils is well understood, little attention has been given to research on how to improve the efficiency of K fertilization in the various farming systems. Emphasis should be given to rates and timing of K application, K dynamics in the soil and recycling through crop residues and other means. Similar attention to that given to N and P fertilizer management in many farming systems now needs to be given to K.

After deficiencies of major nutrient elements identified and corrected by fertilization or liming, crop yields often do not increase as expected and in many cases decline. One increasingly common reason for such decline is the development of nutritional imbalances, particularly in soils with low activity clays such as Oxisols, Ultisols, oxic Alfisols, particularly when the topsoils have coarse textures. Correction of K deficiency often causes Mg deficiency because of an improper K/Mg ratio on the exchange complex (NCSU, 1978). Likewise, nitrogen fertilizer applications may induce secondary acidity which, in turn, may reduce availability of other nutrients. These problems are more severe in areas where fertilizers are available only in one or two formulations and one or both have high residual acidity. Nutrient imbalances are particularly important in the humid tropics, but they are also widespread in soils of the semiarid tropics and acid savannas with low activity clays. Nutrient imbalances are more frequent where only NPK fertilizers are used, or where excessive applications of lime or P are erroneously applied.

For each major farming systemsin which imbalances are suspected, nutrient dynamics need to be determined as a function of time and depth. The effects of recommended fertilizer and lime applications on the status of K, Ca, Mg, S and micronutrients should be determined as well as the critical ratios that indicate imbalances. The possibilities of solving such problems by alterations of fertilizer ratios or by changes in the manufacturing of fertilizers also need to be determined. The imbalances being discussed are not limited to arable or food crops; tree crops and grazing lands may be affected too. Thus, nutrient balance studies should be concerned with the whole nutrient cycles within soils for farming systems of general importance.

4. Sulfur. This element is of special concern because of the increasing frequency of its deficiency and its relationship to N. The decomposition of organic matter releases both N and S in plant-available forms with N:S ratio of about 15 to 1. When N fertilizers that contain no S are applied, the ratio of available N to S often increases sharply and plants suffer from lack of sufficient S to produce the normal N:S ratio of 17:1 in their tissues. With some cereals or oilseeds, such imbalances may actually reduce grain yields even though the N fertilization may increase vegetative growth of the crop.

Blair et al., (1980) emphasized that S deficiencies have been reported throughout the tropics, although the amount of research is rather limited. The increasing use of lime and phosphate fertilizers may decrease S retention in surface soils and may result in less S available for crop growth. Higher analysis fertilizers manufactured at present are devoid of or low in S; deficiencies, therefore, are likely to increase unless S is incorporated into the fertilizers. According to Blair et al., (1980), sulfur fertilization dramatically increases the methionine content of grain in areas where S is deficient, thereby contributing to a better nutritional quality of the product.

Priorities for sulfur research are:

a) Development of appropriate chemical methods to estimate S availability.

b) Coordinated investigations of the effect of S fertilization on crop yield and quality.

c) Selection of varieties which are efficient in the use of S.

d) Study S reactions in dryland and wetland soils as to efficiency of fertilizer S sources, leaching and residual values and long-term effects.

e) Methods of incorporating S into fertilizer formulations for use in the tropics.

5. Micronutrients. Deficiencies of Zn, Fe, B, Mn, Cu and Mo are becoming increasingly important constraints in the developing world because 1) the increasing use of NPK fertilizers raises yield levels and consequently plant micronutrient requirements, and 2) the expansion of the agricultural frontier into marginal soils, where micronutrient limitations are generally more acute. The basic problem is a paucity of information about micronutrient levels in the soil and micronutrient requirements of plants to be grown.

The widespread nature of micronutrient deficiencies can be illustrated by comments from recent reviews. Zinc is probably the most limiting micronutrient in terms of areal extent, because it occurs both in acid and calcareous soils. Sanchez and Cochrane (1980) estimate that 50% of tropical America's land area (approximately 740 million hectares) suffer from some degree of Zn deficiency. Large areas devoted to lowland rice in Asia are also Zn deficient, including many soils that are kept constantly flooded (Ponnamperuma, 1977). About half of the soils of Brazil are deficient in Mo for legume crops (J. Dobereiner, personal communication). Poor rhizobium-legume symbiosis is often due to unidentified micronutrient deficiencies, which often leads to pasture degradation (Hutton, 1979). A review by Lopes (1980) notes that Ultisols in the Amazon jungle of Peru are deficient in B, Cu and Mo. Volcanic ash soils, particularly the older ones, are often deficient in Mo. Overliming of Entisols, Oxisols and Ultisols in Africa have resulted in deficiencies of Mn and Zn. On the other hand, Mn toxicity has been observed in the acid Entisols. Boron deficiencies are extensive in Africa on hydromorphic soils and Alfisols. Molybdenum deficiencies are a problem in acid sandy soils in Africa. Iron deficiencies of paddy rice have been found in the calcareous soils where low organic matter contents limit soil reduction.

Deficiencies of micronutrients in legumes must be studied with plants inoculated with rhizobia, because the legume-rhizobia symbiosis often required more Mo, Fe, Co, S and Ca than the plant alone.

Identification and solution of micronutrient deficiencies require sophisticated laboratory facilities and extensive field experiments. Such investigations should include:

a) Determine of soil tests or plant tissue critical levels (deficiency, toxicity and balance) of the various micronutrients for the various crops to be grown in a region.

b) Correlate micronutrient differences with natural soil classification systems or technical interpretations thereof.

c) Determine appropriate rates, timing and methods of applications of the necessary micronutrients, estimating the length of their residual effects and possible interaction with other plant nutrients. Monitoring of possible buildups of B and Cu that may reach toxic levels should be included.

d) Determine appropriate ways of incorporating micronutrients in fertilizer combinations.

D. Research Components for Utilizing Biological Resources

The fourth group of research priorities encompasses those that include a direct plant input as a source or expediter of improved plant nutrition. Biological nitrogen fixation is of overwhelming importance, but other aspects of a more fundamental nature have been identified by the assessment studies. In addition, soil-borne pathogens, including nematodes are important biological constraints. They will not be discussed in this paper because this constraint is generally considered the province of plant protection.

1. Biological Nitrogen Fixation (BNF). Among the soil nutrients, only N has natural biological mechanism for replacing crop removal and losses from the soil. Atmospheric N can be transformed into ammonia by N fixing bacteria. Biological N fixation together with photosynthesis are among the key processes responsible for the maintenance of life on earth. The exploitation of BNF is gaining increasing importance because it replaces fossil fuels in supplying crops with N. The principal mechanism is the legume-rhizobium symbiosis. The associative symbiosis of bacteria and pasture grasses as noted by Weier and MacRae (1981) may hold promise. Another important mechanism is asymbiotic fixation in the soil and rhisozphere of plants, which is of particular importance in flooded soils. The use of Azolla-Anabaena symbiosis between a blue-green algae and an aquatic plant has recently been introduced from Vietnam and China to the rest of the world. The N fixed by Azolla is incorporated into the soil by mixing the plants into the topsoil.

A major advance in increasing BNF for marginal soils is the existence of differential tolerances by rhizobium strains to adverse soil factors such as soil acidity, salinity, temporary flooding and even high soil N content (Peter Dart, personal communication). Some priority research areas suggested in the Soils Constraints Conference (App et al., 1980) and by the Bonn study are outlined below:

a) Select rhizobium strains to match soils and local cultivars.

b) Review the needs for P and Mo fertilization of rhizobia and associated legumes.

c) Develop superior yielding varieties of grain legumes more capable of being better partners with improved rhizobia.

d) Develop legume-based pasture production systems for those soils marginal for food grain production.

e) Develop mycorrhizal inoculants for legumes to enhance their P uptake.

f) Develop improved methodology for estimating non-symbiotic N fixation.

g) Select variant forms of Azolla and blue-green algae suited to specific rice soils.

Mention should be made of the possibility of drastically changing the genetic makeup of cereals in order for them to supply sufficient energy to the roots to support symbiotic or associative N fixation. This issue was featured prominently in the earlier studies but not in the three 1979 studies. This is probably a reflection of more urgent needs in tropical areas. Such long-term low probability of success research, however, merits continued attention by advanced laboratories around the world, but no longer appears as a high priority item for problem-oriented plant nutrition research in developing countries.

2. Organic residue utilization. The rising cost of fossil fuels draws attention to the need to make better use of organic materials from agricultural residues and other sources for supplementing the supply of plant nutrients available from the soil and from inorganic fertilizers. Increasing petroleum costs, however, also increase the demand for organic residues for direct conversion into liquid fuel. Consequently, competition between agriculture and industry for manures and crop residues is an important consideration.

Other potential uses of organic materials are in mulching for moisture management and soil structure maintenance and the use of green manuring to increase plant nutrient availability. Currently, these potentials are inadequately exploited. The Soils Panel of the Bonn Conference suggested the following areas of research emphasis:

a) Improve the recycling of organic materials, including better collection, conservation and application of organic materials to be returned to the land, such as crop residues and animal manures.

b) Compare the benefits of alternative sources of plant nutrients, the interaction between organic and inorganic nutrient inputs, as well as the real costs of using organic materials as fertilizers.

c) Determine the factors which limit adoption of effective organic materials to important farming systems.

3. Photosynthetic efficiency. Plants capture less than 3% of the solar energy they receive in the process of photosynthesis. The World Food and Nutrition Study suggests that the theoretical maximum is 12% and that both basic laboratory and agronomic research could significantly increase the rate of solar energy conversion. The Michigan-Kettering study and the World Food and Nutrition Study emphasized the following priority aspects (Brown *et al.*, 1975; NAS, 1977b):

a) Slowing photorespiration in C_3 crop species.

b) Increasing the efficiency of dark respiration.

c) Investigating C_3 and C_4 species differences.

d) Improving plant architecture and transport of photosynthate.

This priority area, however, received a rather different agronomic emphasis at the Bonn Study (Wolff, 1979). The suggested areas of work are:

a) Appropriate multiple cropping systems for specific environments to take full photosynthetic advantage of available solar energy, soil and water resources.

b) Increase the capability of root and tuber crops to store photosynthate.

c) Breed and select crop plants with improved architecture for capturing solar energy and storing photosynthates.

d) Plant well-adapted tree crops that can rely on stored soil moisture and photosynthate reserves to withstand periods of environmental stress.

e) Select varieties of crop plants with high tolerance for drought and other environmental stresses.

This is the only research component where real divergence was observed among studies as to the means to accomplish the same objective.

4. Rhizosphere effects. Five studies identified research on plant-soil micro-organism interactions (in addition to BNF) as a major priority component. The Michigan-Kettering and World Food and Nutrition Study emphasized a variety of aspects, while the Soil Constraints, North Carolina and Bonn Studies concentrated on the potential of endomycorrhizal associations.

The rhizosphere is a complex and ever changing region of the soil in which microflora and plant roots interact with each other. This is "where the action is" in terms of plant nutrient uptake because nutrient ions are affected by a different chemical composition from the rest of the soil resulting from root secretions and microbiological activity (NAS, 1977c). Our understanding of this crucial region is limited, aside from BNF. Two major considerations are the potential increases in nutrient uptake via mycorrhizal associations and a better understanding of nutrient uptake in the rhizosphere.

Endomycorrhizae enter into symbiosis with roots of most important crop plants. Fungal hyphae act essentially as extension of the plant's root system, increasing the volume of soil from which the plants can absorb relatively immobile nutrients, particularly P. Most annual and perennial crops are mycorrhizal and the benefits of such associations are already taking place. A classic example of cassava, a species that has a very high P requirement in culture solution but a very low requirement in soil culture because of endomycorrhiza infection (Yost and Fox, 1979).

The principal research aspects are:

a) Develop practical methods of inoculating plants with improved mycorrhiza strains under field conditions.

b) Determine whether inoculated strains persist and improve nutrient uptake.

c) Determine the importance of rhizosphere reactions such as "hydrogen leaking" that may affect or improve nutrient uptake (Israel and Jackson, 1978).

5. Basic stress physiology and genetics. The physiological mechanisms that govern plant tolerance to soil stresses are not sufficiently well understood (Wright, 1976; Jung, 1978). It is known that some varieties require less P for maximum yields than others of the same species but the mechanisms are poorly understood. Likewise the inheritance mechanisms of tolerance to adverse soil stresses is not sufficiently documented. Basic research in these aspects have been identified by the Michigan-Kettering study as a priority research component.

E. Research Components for Alleviating Physical Soil Constraints

Four priority research components for preventing or overcoming soil physical constraints to improved plant nutrition have been identified by the different studies: Improved water management in rainfed farming systems, prevention and control of soil erosion, surface crusting and other mechanical impedances, and land clearing methods. These constraints are receiving increasing attention in the tropics, particularly in areas where physical soil limitations are more critical than chemical, such as in West Africa. Major reviews on the subject have been produced by Greenland and Lal (1977) and Lal and Greenland (1979).

1. Water management in rainfed farming systems. Rainfed farming systems often suffer from temporary periods of water stress because of the vagaries of rainfall distribution during the rainy season. The Bonn study notes that the failure to make the most of the available precipitation is exacerbated by losses via runoff, and leaching and subsequent damage to the environment. Nowhere is this constraint more critical than in the semiarid tropics. This region is also fortunate to begin experiencing a breakthrough on how limited and undependable rainfall can be utilized in a way that two good crops can be grown per year where only one marginal crop could be grown before. ICRISAT's Farming Systems Program and related national programs are showing the way for one major soil type, the deep Vertisols (Krantz et al., 1978). Similar technology needs to be developed for areas with different soils, particularly the sandy and plinthic Alfisols of the Sahel and Sudan savanna regions of West Africa. The Bonn Study identified the following aspects as key ones to improve water utilization in rainfed semiarid farming systems (Wolff, 1979):

a) Technologies for collecting, using and conserving water to increase crop production, including "water harvesting."

b) Effective surface drainage techniques especially for heavy soils to eliminate excess surface water during periods of intense rainfall and deliver it to storage tanks.

c) Adapting animal-drawn equipment to conduct tillage operations at low cost.

d) Cooperative efforts by local farmers to develop and manage watershed systems, including storage tanks for supplemental "crop saving" irrigations.

e) Labor intensive technologies for soil, water and crop management by small farmers.

2. Erosion prevention and control. Clearing and cultivating land exposes the soil to the erosive effects of wind and rain, and can lead to accelerated erosion, reducing the productivity of the soil and causing siltation of streams and reservoirs. This, in turn, may result in flood damage downstream. Overgrazing, exploitative logging practices and construction work also lead to accelerated erosion. Although the immediate effects of erosion are most spectacularly visible in the steeplands and the semiarid tropics, it is a phenomenon common to all areas other than those river basins where lowland rice is produced and where carefully controlled water use and distribution systems are well established. Although the damage caused by severe erosion is easy to visualize, development agencies find it difficult to estimate the value of soil conservation programs that will prevent such damage.

The basic principles of soil erosion prevention and control are well known and can be summarized in one sentence: Keep the soil covered with a plant canopy at critical times. Much work is needed, however, to translate this principle into viable practices in the developing world.

Lal (1980) reviewed the impressive amount of existing data on soil erosion losses, particularly in Africa, and noted the depressing fact that very little has been done about preventing them. He expressed the need to become quantitative about erosion losses and proposed the use of the "Y_{50}" parameter, i.e., tons per hectare of soil loss required to decrease yields by 50 percent. Priority should be given not only to preventing erosion but also to reclaim eroded land economically.

Research needs are both basic and applied. The basic information currently used in the tropics is that developed in the temperate region. Major differences in climate and soils suggest that it would be mere coincidence if the empirical relationships developed in one climatic region can be directly transferred to others. The specific research needs outlined by Lal (1980) are:

a) Wind erosion, an essentially neglected area in the tropics.

b) Develop inexpensive and effective control methods for gully erosion.

c) Rainfall parameters affecting erosivity such as drop size, distribution, kinetic energy and momentum of tropical storms should be determined to quantify the erosivity of tropical rains.

d) Basic and applied aspects of erodibility of key soils.

e) Soil management practices to prevent erosion, such as zero tillage.

f) Integrated watershed management.

In addition, the authors suggest that methods be developed to demonstrate the benefits of soil conservation in the various agroecological zones of the developing world.

3. Mechanical impedance. Different kinds of mechanical impedance seriously affect food production in the tropics. Perhaps the most damaging is the widespread surface crusting or capping common in many soils of the semiarid tropics, and to a lesser extent of other regions. Surface crusting can retard or delay seedling emergence and result in poor plant stands. Tillage-induced compaction of the topsoil often occurs when excessive land preparation takes place on soils without strong granular structure. Subsoil hardpans may also develop as a result of mechanical tillage. Articles by Nicou and Charreau (1980) and Taylor (1980) provide an up-to-date review of these limitations, including the soils where they are likely to occur. Nicou and Charreau (1980) note that the soils most susceptible to mechanical impedance have topsoils with kaolinitic clay mineralogy, less than 18% clay and probably less than 5% organic matter. They are mostly classified as Alfisols and Ultisols. The main research issues include:

a) A better understanding of the process of surface crusting and soil hardening under semiarid tropical conditions in relation to soil characteristics.

b) Development of management systems to prevent compaction. In the humid tropics this may include minimum or zero tillage, but the hardness of many soils of the semiarid tropics at the onset of the rainy season requires the use of mechanical tillage.

c) Train extension specialists in preventing excessive tillage, particularly with heavy machinery which often pulverizes the soils leading to compaction, runoff and erosion.

d) Study the possibility of selecting crop varieties for the ability of their roots to penetrate hard subsoil layers.

It should be noted that the danger of laterite or plinthite formation is not mentioned as a constraint by any of the seven studies. Tropical soil scientists are well aware of the limited importance of this phenomenon, but unfortunately the popular press often mentions laterization as a major hazard (Sanchez and Buol, 1975).

4. Land clearing methods. Large scale deforestation is taking place in many humid tropical areas with the use of mechanized land clearing. The rudimentary bulldozer clearing technologies employed are resulting in major physical damage to the soil in terms of topsoil displacement and surface soil compaction. This is particularly evident in certain transmigration areas of Indonesia and in parts of the Amazon.

Research conducted in the Amazon and elsewhere shows that the traditional slash and burn method is a better way to clear tropical forests than any mechanized method. With slash and burn, the nutritive value of the ash becomes free fertilizer and there is no significant topsoil displacement or immediate compaction problems. Yields of most crops and pasture species are higher in areas cleared by slash and burn than those cleared by bulldozing (Seubert et al., 1977; Sanchez, 1979). The detrimental effects often last for several years. Unfortunately it is no longer sufficient to recommend slash and burn clearing because the pressure of land clearing in many areas is so high that it has to be done by mechanized means. The main issues are:

a) Develop alternative mechanized land clearing techniques that minimize the damage to soil properties. Combinations of mechanized clearing with burning are also worthy of investigation.

b) Determine appropriate land preparation and crop establishment methods for sustained production to follow the different clearing methods used.

c) Develop management practices for reclaiming abandoned land cleared by mechanical means.

d) Train bulldozer operators and colonization project managers on how to minimize soil damage while clearing tropical forests.

F. Research Components Related to Improving Farming Systems

All studies place special emphasis on integrating the information generated into new or improved farming systems capable of sustained and profitable production. The choice of farming systems is quite variable within a region and is very dependent on market demand or opportunities, farming tradition and government policies. The invention of new farming systems is not envisioned by the authors of this report as an appropriate research goal in most circumstances. The improvement of present farming systems by the incorporation of new technology components is usually the most effective approach and is strongly recommended as a key priority research area. New technology that produces improved plant nutrition must fit with other aspects within a farming system, not only the purely agronomic ones such as pest control, but also socioeconomic ones.

The various assessment studies have highlighted six research components as specific areas of attention within the general scope of farming systems. Some will be discussed in less detail than the previous one because many of them are better described within the context of management systems for specific agroecological zones.

1. Sustained production in Oxisols and Ultisols. Five of the studies strongly recommend the development of continuous farming systems in acid, infertile soils regions of the humid tropics presently under shifting cultivation. Population pressures are destroying the stability of traditional shifting cultivation systems in much of the humid tropics. The change from shifting cultivation to some form of permanent farming system is probably drastic enough to be considered the development of a new farming system. Substantial research has been conducted primarily in the Amazon and in West Africa that demonstrates the feasibility of replacing shifting cultivation with continuous agriculture. Continuous cultivation systems of Ultisols in the Amazon of Peru have been developed by North Carolina State University's Tropical Soils Program in Yurimaguas, Peru where three crops a year are grown continuously with judicious use of plant nutrient input. A total of 20 continuous crops have been grown to date and yields are increasing rather than decreasing because of experience (Sanchez, 1977, 1981; Valverde and Bandy, 1981). Examples of long-term livestock production based on grass/legume pastures have also been developed in the Amazon of Peru (Toledo and Morales, 1979). The IITA Farming Systems Program has also developed means for continuous crop production for West African Alfisols, based primarily on preventing the deterioration of physical soil properties. These two different approaches reflect the differences in constraints between Ultisols of the Amazon and Alfisols of West Africa. In the former case, chemical constraints are the main ones, while in the latter soil physical constraints predominate.

Much of this technology needs to be validated in other areas both in agronomic and economic terms. The specific items are better described with the content of the humid tropics agroecological zone.

2. Multiple cropping. This priority research component was included in all of the studies. The principal issue is to gather more fundamental information as to how plants interact when two or more species are grown at the same

time in terms of their nutritional relationships. Although most food crops in Africa are grown in intercropped combinations most of the fertilizer response work has been conducted in monocultures. Much more work is needed on how to fertilize multiple cropping systems. For additional information, the readers are referred to a book edited by Papendick et al., (1976).

3. Agroforestry. Agroforestry is a general term encompassing the planting of annual crops and/or pastures with trees, either intercropped or in sequence (King and Chandler, 1978). Consideration of this topic as a priority research did not surface until 1979. The increasing importance of agroforestry is partly due to the potential benefits of including tree crops for sustained farming systems in the humid tropical areas with little input, decreasing erosion hazards and the need to counteract the severe deforestation common in many parts of the semiarid tropics and in the steeplands. In the latter two regions, agroforestry is envisioned by many as the main means for alleviating the fuelwood crisis (Hanson, 1979; Leach, 1979). The "agro" part of agroforestry (its food production potential) is also of considerable importance.

A recent review of soils research in agroforestry (Mongi and Huxley, 1979) suggested several priority areas, among which the following seem particularly relevant to plant nutrition:

a) Determination of nutritional requirements and stress tolerance of potentially important tree crops for agroforestry purposes.

b) Identify the most promising combinations of annual crops with tree crops, pastures with tree crops and annual crops/pasture/tree crop successions for different environments.

c) Elucidate the nutritional dynamics of interacting root systems and their role in nutrient cycling.

Agroforestry is at present a very popular issue. Unfortunately writings about its importance exceed the generation of hard data.

4. Intensive fertilization of high value crops. This item was considered high priority only by the Cornell NSF study (Lathwell, 1975). It is aimed at improving the efficiency of foliar and soil fertilizer applications of horticultural and other high value crops to ensure high yield and high quality. The relevance of this topic appears to be of limited scope in developing countries, although local economic importance may be high, for example chrysanthemum production in the Bogotá area for export purposes.

5. Management of irrigated farming systems. Although no figures are available, it is apparent that a large proportion of the fertilizers used in developing countries for food crop production is applied in irrigated farming systems. Although such systems are found in all rainfall regions, particular emphasis has been given to improve the management of irrigated farming systems in arid regions where large irrigation programs are underway. The yield potential of irrigated areas is enormous as they are farmed under high solar radiation, relatively low night temperatures that decrease crop respiration, and low atmospheric humidity that decreases the incidence of pests and diseases.

Water management is the paramount constraint, while nitrogen and salinity are the most widespread plant nutritional constraints. Very high yields of wheat, rice, sugar cane and many other crops are produced in irrigated arid areas of Pakistan, India, Egypt, Peru, Mexico and many other countries. The quantities of N fertilizers required are often very high because of the high yield potential triggered by high solar radiation and the considerable leaching losses of N under poor water management. Fertilizer applications, mainly N, are conducted at the higher reaches of the response curve, suggesting important fine tuning mechanisms (Sanchez, 1976).

Soil salinity reduces plant yields, renders irrigation enterprises uneconomical and causes in its extreme form the complete loss of agricultural production potential. As mentioned before, the causes of salinity have been thoroughly studied and are probably well known in most affected areas. However, management and remedies are still debated and reclamation measures are frequently expensive and even unsuccessful in many cases.

The problem to be coped with is in the forecast of conditions resulting from irrigation and in the timely evaluation of salinity hazards. This required elucidation of the interdependencies between climate, soil, water, natural drainage, cropping patterns, alkalinity tolerance and farm management.

The key to improved plant nutrition in irrigated arid regions is primarily improved water management. The Bonn Soils Panel Report (Bentley, 1979) indicates that the inefficiencies of irrigation are of rapidly increasing concern and solutions will depend on new technologies as well as social changes. Because water is free to farmers or has only very modest charges in most irrigation schemes, the efficiency of water use and distribution systems is generally very low. Practical ways and means of reducing seepage losses, wasteful use and unnecessarily slow water delivery are urgently needed. Social research is required to develop techniques to win and expedite acceptance of land consolidation and canal rationalization schemes which would increase irrigation efficiencies and crop yields.

For irrigation, the Bonn Conference recommended the following specific research needs:

a) Improved design criteria for new or renovated irrigation projects whether for gravity sprinkler or drip irrigation methods. Requirements will vary considerably depending on soil characteristics.

b) Methods to attract and retain farmer participation in land consolidation and/or drainage projects under differing social and soil conditions.

c) Development of improved national, regional and local mechanisms for development and maintenance of irrigation schemes.

6. Low chemical input farming systems. Four studies placed special emphasis on developing or adapting farming systems that use lower levels of fertilizer inputs than previously considered (Table 6). This approach is in response to the challenges posed by the 1973 energy crisis and has been alluded to in prior portions of this report. Sanchez and Salinas (1981) have reviewed this subject and their conclusions are summarized in the subsequent paragraphs.

Low input technology for marginal soils of the tropics can be defined as a group of practices that can produce about 80% of the maximum yields through the most efficient use of soils, stress-tolerant germplasm and chemical inputs. The term "low" is used in contrast with "high" chemical input technology where the application of fertilizers and amendments largely eliminate plant nutritional constraints.

The identification of plant species and ecotypes tolerant to the main soil stresses allows the development of low input soil management systems for marginal regions where socioeconomic constraints prevent the widespread application of large quantities of lime and fertilizers. The basic approach is to use plants adapted to the soil constraints, maximize the efficiency of fertilizers and lime use needed to produce about 80% of the maximum yields, and take advantage of favorable attributes of certain marginal soils. Several technology components are reasonably well identified and could be used as building blocks for specific management systems. Sanchez and Salinas (1981) suggested attention to the following aspects for acid, infertile soils of the humid tropics and acid savannas of Latin America. Although these aspects will vary for other agroecological zones, the following list provides an example of low input strategies:

a) Select lands dominated by nearly level, well drained Oxisols or Ultisols without steep slopes and identify the major soil constraints encountered.

b) Select species and varieties of annual crops, pastures or tree crops that can tolerate a reasonable degree of Al toxicity, low available P levels and/or Mn toxicity, as being well adapted to climatic, insect and disease stresses.

c) Land clearing methods in rainforests that include burning in order to take advantage of the fertilizer value of the ash, minimize soil compaction and permit the rapid establishment of a crop or pasture canopy to decrease erosion hazards. Land clearing methods in the savannas are less complicated but should also aim at the quick establishment of a plant canopy.

d) Low cost pasture establishment techniques should include the introduction of improved species into native savanna, its gradual replacement, low density seeding methods and crop-pasture relay intercropping. Pasture maintenance techniques must consider the frequency of fertilizer applications.

e) Further soil cover protection can be obtained by mulching annual crops, although the results are not always positive. Intercropping and agroforestry combinations are poorly characterized and quantified.

f) Soil acidity constraints can be attenuated without massive lime applications by 1) the use of plant species and varieties tolerant to aluminum and manganese toxicities, 2) low rates of lime to satisfy the Ca and Mg requirements of plants, 3) lime to decrease Al saturation below toxic levels, if needed, and 4) promote the downward movement of Ca and Mg into the subsoil.

g) Efficient phosphorus management in these soils should include 1) determining the most appropriate combination of rates and placement methods that enhance initial and residual effects, 2) improve soil fertility evaluation methods for making fertilizer recommendations, 3) use low cost sources, such as phosphate rock, 4) select species and varieties that grow well at lower levels of available soil phosphorus, and 5) explore the practical possibilities of mycorrhizal inoculation to increase phosphorus uptake by plants.

h) The main low input technologies to manage low native soil fertility center on 1) the maximum use of nitrogen fixation by legumes using acid-tolerant rhizobia, 2) increasing the efficiency of nitrogen and potassium fertilization, 3) identifying and correcting sulfur and micronutrient deficiencies, and 4) promoting nutrient recycling.

G. Technology Transfer Needs

Although the seven studies described in Table 6 were oriented primarily toward research priorities and the participants were mostly research scientists, major emphasis was given to the need of strengthening the technology transfer processes in all of them and the ones predicted as output of the proposed research components. Major importance is attached to four priority components.

1. Validation and adaptation of research results. Regardless of whether research was conducted at experiment stations or in farmer fields, the ensuing technology needs to be validated and if judged promising, adapted to local conditions. Major emphasis should be given to characterizing the differences in soil, climatic and socioeconomic constraints between the place where technology originated to where it will be validated. Soil characterization and its interpretation in agronomic terms is considered the cornerstone for the successful transfer of plant nutrition and soil management technology. In effect this is the "bottom line" of all the research priorities. Technology validation is considered the responsibility of the national institutions.

2. Training. The training of soil and plant nutrition specialists at levels ranging from technicians formulating fertilizer recommendations or managing irrigation systems to sophisticated research scientists is considered of high priority by most study groups. There are considerable numbers of soil scientists scattered throughout the tropics but most of them are not as productive as they should be. Part of the reason is that they are not trained in the techniques for relevant research programs. Formal university training is often very specialized with the scientists calling themselves pedologists, soil physicists, soil chemists, soil microbiologists, soil fertility specialists and plant physiologists. There is a need for a broader appreciation of the management of soils and plant nutrients under tropical conditions. This constraint has been somewhat alleviated by formal graduate training offered at some universities on soil management in the tropics, often with an opportunity to conduct the thesis research under tropical conditions. Working as part of a multidisciplinary team helps tremendously. Training, therefore, should aim at giving scientists and technicians a broad appreciation of the main research constraints, identified in this chapter as well as to gain in-depth experience in one particular area.

Although training needs could be described in more detail, it appears sufficient to state in this report that training national institution personnel in soil and plant nutrition ranks the same importance as international centers attach to traiining as part of their overall program. The situation is also analogous to the low numbers of properly trained rice or cassava workers before IRRI and CIAT started their training programs.

3. Develop effective systems for fertilizer recommendations to farmers. Although this issue has been alluded to in the soil fertility evaluation section, it deserves emphasis here, as the key to increased plant nutrition effectiveness largely lies with the acceptance of appropriate fertilizer and other agronomic recommendations by farmers. In most developing countries, soil fertility evaluation services need considerable strengthening in order to provide this function in a technically correct and timely fashion. Many efforts are presently limited to persuading farmers to use fertilizers for the first time. Emphasis must be given to optimizing the return of fertilizer investment. Fertilizer response trials must be performed in well-characterized soils in order to establish the limits of extrapolating this information. Soil fertility specialists need to include risk analysis in addition to the usual cursory economic interpretation of yield response data. Fertilizer recommendations must then be coordinated with the availability of supplies. It should be emphasized that fertilizer companies, either private or governmental, have played a vital role in promoting fertilizer use and making recommendations to farmers, as a means for filling the gap of ineffective fertility evaluation services. The natural bias toward the companies' marketing interest, however, often lessens objectivity in their recommendations.

4. Information services. The need for an efficient way of exhanging soil-plant nutrition information throughout the developing world is widely recognized. Communication of research results is often hampered by the different nomenclature and laboratory procedures used. Of equal importance is the lack of straightforward documentation services such as those developed for specific commodities by several international centers. The developing of a computerized data base accompanied by abstracting services, newsletters, working groups and conferences is also considered a high priority item.

H. Towards a Systematic Approach for Plant Nutrition Research

The 32 research components interact with each other and also carry various degrees of relevance for different agroecological zones of the developing world. Nevertheless, a general theme underlies most of them, which could be called a fertilizer management strategy.

For a specific agroecological region, knowledge base of soil properties and plant nutrition constraints is needed. There is little value in conducting expensive fertilizer trials if little is known about the properties of the soil. Plant nutritional constraints do not necessarily have to be resolved by the application of fertilizers and amendments; varieties and species that are tolerant to various soil stresses can now be used. Their use would decrease but not eliminate the need for fertilizer inputs, thereby increasing the efficiency of such inputs. More attention needs to be given to the different sources of nutritional inputs such as organic manures, crop residues, BNF and their interactions with inorganic fertilizers. Long-term research is needed both in properly evaluating the efficiency of inputs that can provide a considerable residual effects and in identifying imbalance problems or the development of secondary acidity or salinity. Physical soil constraints are often more severe than chemical ones; if not prevented or alleviated, little improvement in plant nutrition efficiency will occur in spite of major efforts in fertilizer use. Plant nutrition problems are therefore, best studied within a farming systems context. The recommendations arising from such research must also be accompanied by the availability of supplies and properly trained technology transfer personnel.

VI. SUGGESTED RESEARCH FRAMEWORK

A. Rationale for the Agroecological Zone Approach

The previous chapter describes the principal research needs related to plant nutrition arising from the consensus of a large number of scientists who were involved in the seven studies. The 32 research components were not weighed in terms of their relative importance, potential impact, magnitude of effort or other criteria. This chapter attempts to provide such an evaluation, drawing heavily from the conclusions of the three studies conducted in 1979 as well as additional information gathered by the authors of this report.

There are many ways of ranking priorities and they are all essentially judgmental. The most direct approach would be to rank the 32 individual components according to several criteria. The obvious limitation of this approach is that most of the components interact with others and it is difficult to assess their potential impact as discrete entities. The Soil Constraints, North Carolina and Bonn studies decided to arrange the priorities by agroecological zones in recognition that priorities differ in major regions of the developing world, although many are important to all regions. The agroecological zones were defined in broad terms to distinguish major regions of the developing world with similar <u>kinds</u> of soil and plant nutrition constraints, although the <u>degree</u> of manifestation of such constraints varies considerably within an agroecological zone. Thirteen agroecological zones were identified by the North Carolina study to cover the developing world, both tropical and temperate (NCSU, 1979). The following criteria were developed and used in that study to identify the priority agroecological zones:

1. Relevance to the overall goal (increased agricultural production while conserving the natural resource base).
2. Direct benefits to rural and urban poor.
3. Amount of land in the agroecological zone.
4. Population presently in the zone.
5. Population the zone can potentially support.
6. Present poverty level (the inverse of the gross national product).
7. Need for research.
8. Availability of potential collaborators.
9. Technical feasibility of research.
10. Socioeconomic feasibility.
11. Ongoing development projects.
12. Logistical problems involved.

Five priority agroecological zones were identified by the North Carolina study, several of which are amalgamations of the original thirteen. The Bonn study adopted these results, modified and expanded them. In effect, the three 1979 studies built on each other, with the ideas and framework gathering sharper focus.

Without resting importance to other parts of the developing world, these studies suggest that research on soil constraints and plant nutrition be concentrated on five priority agroecological zones: The humid tropics, acid savannas, semiarid tropics, wetlands and steeplands. These are not listed in order of importance but represent as a group the priority target areas for soil constraints and plant nutrition research in the developing world. Figure 1 drawn from North Carolina study shows the approximate location of the agroecological zones.

B. Assessment Parameters

The following sections discuss each of the five agroecological zones, indicating the priority ranking of each of the 32 research and development components (Table 7). Table 8 ranks the agroecological zones as a whole and Table 9 the main research components in terms of six criteria developed by the Bonn Conference soil panel report (Bentley, 1979):

1. Impact in the short-term, reflecting low, medium or high probability that research results can be produced and translated into applicable technology in a period of less than 10 years.

2. Impact in the long-term. Same as above but considering a time span of 10 to 20 years.

3. Magnitude of cost only provides relative order of magnitude and needs further qualification in terms of the number of research units envisaged, staff and equipment, geographical spread and other factors.

4. Ease of transfer outlines the expected pace of technology transfer considering primarily socioeconomic constraints.

5. Payoff estimates the returns of research in terms of improving agricultural production and/or the protection of the resource base.

6. Existing capabilities outline the present degree of capability and competence in a particular area by national and international research institution in a general way.

It should be emphasized that the order of discussion of the agroecological zones does not imply a priority ranking among them.

C. The Humid Tropics

The humid tropics comprise the portion of the world with relatively constant temperatures and no more than a three-month consecutive period where evaporation exceeds precipitation. The humid tropics cover approximately 1500 million hectares. The geographical extent is shown in Figure 1. Many of these fragile but potentially very productive ecosystems are presently under shifting cultivation and are experiencing large settlement attempts. Together with acid savannas, this is where much of the 200 million hectares of new lands needs to be cleared during the remainder of this century (FAO, 1979b).

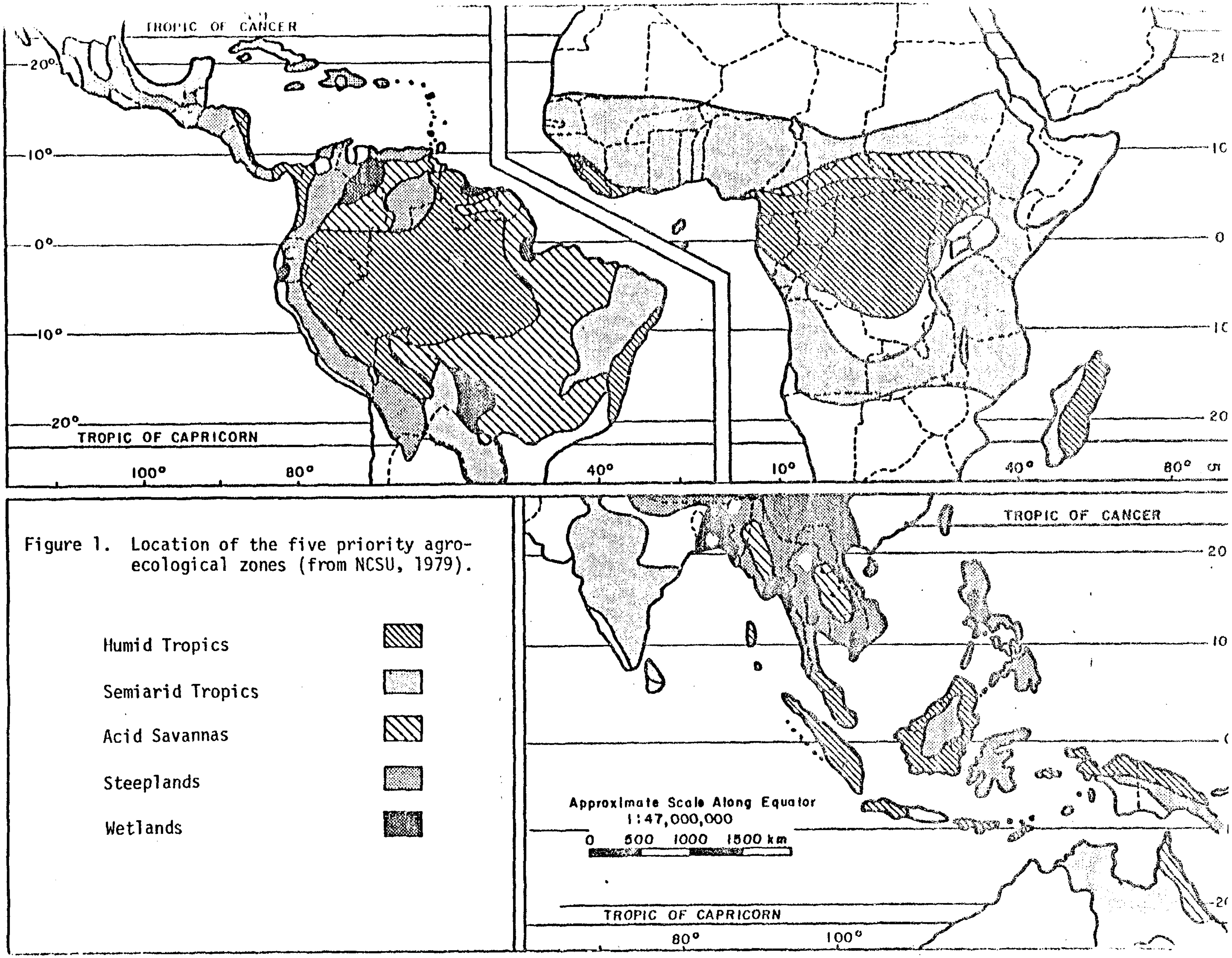

Figure 1. Location of the five priority agro-ecological zones (from NCSU, 1979).

There is reasonably good knowledge on how to produce perennial export crops in the humid tropics, but very little on how to do likewise for annual crops and pastures. Continuous annual crop production on tropical Oxisols and Ultisols has been attempted for decades. After a classic failure of trying to transplant temperate region high energy technology in what is now Zaire in the 1930's, progress has been virtually limited to small areas with ample available capital for export crops. Systematic research toward developing realistic soil management practices for food production in tropical Ultisols and Oxisols is underway at a few locations with significant international support. Where present population densities are low, national governments do not feel the immediate political pressures to develop their "new" lands until it is too late. Crash programs or forced colonization projects without a sound agronomic base are then launched and usually fail.

These attempts are now proceeding at an unprecedented rate in many parts of the humid tropics. Significant proportions of the Amazon basin are being rapidly settled, as new road networks or petroleum drilling operations attract people from crowded areas of the Andes and Northeast Brazil. Peru and Ecuador are probably experiencing the greatest pressures, as well as certain parts of Brazil. The Indonesia Transmigration program is shifting about 2.5 million people from overcrowded Java and Bali to Sumatra, Kalimantan and other islands.

This rapid growth has caused major worldwide ecological concerns about deforestation in the humid tropics. Many of these concerns have no scientific base, e.g., worldwide oxygen depletion, increases in CO_2, transformation of the soil into laterite, or into a desert. Nevertheless, it is most unwise to destroy natural ecosystems and replace them with unstable, unproductive farming systems. There are real dangers of soil erosion, changes in the hydrological cycle and others if this happens in a large proportion of the humid tropics. This problem cannot be solved by decrees even if strongly enforced by governments. Land-hungry people will go to empty areas. The development of a set of practices of make these acid infertile soils productive on an economically and ecologically sound basis is critically needed in order to assure that each hectare of land that is cleared remains productive. Given the low native fertility of most humid tropical soils, proper plant nutrition technology is an essential prerequisite for achieving the above goal.

Table 7 shows that 16 out of 32 research components are high priority in the humid tropics:

1. Soil characterization and classification
2. Soil classification for plant nutrition
3. Soil fertility evaluation
4. Selecting germplasm tolerant to soil stresses
5. Management of soil acidity
6. Nitrogen fertilizer efficiency
7. Phosphorus fertilizer management
8. Biological N fixation
9. Land clearing methods
10. Sustained production systems in Oxisols and Ultisols (involving annual crops, grass/legume pastures, and tree crops)
11. Agroforestry (combinations of the above)

Table 7. Priority rankings of research components by agroecological zones (0 = none, 1 = low, 2 = medium, 3 = high

Research and Development Components	Humid Tropics	Semi-arid Tropics	Acid Savannas	Wetlands	Steeplands
A. RESOURCE APPRAISAL					
1. Soil characterization and classification	3	3	3	3	3
2. Soil classification for plant nutrition	3	3	3	3	3
3. Soil fertility evaluation	3	3	3	2	3
4. Fertilizer marketing, distribution and use	2	2	2	2	2
5. Fertilizer manufacturing technology	2	1	2	2	1
B. STRESS FACTORS					
1. Selection of germplasm tolerant to soil stress	3	2	3	3	2
2. Management of soil acidity	3	1	3	0	1
3. Salinity	0	2	0	2	0
C. NUTRITIONAL CONSTRAINTS					
1. Nitrogen fertilizer efficiency	3	1	2	3	1
2. Phosphorus fertilizer management	3	1	3	0	2
3. Potassium and nutrient balance	2	1	2	1	1
4. Sulfur	2	1	3	2	2
5. Micronutrients	2	1	3	2	2
D. BIOLOGICAL CONSTRAINTS					
1. Biological nitrogen fixation (BNF)	3	3	3	3	3
2. Organic residue utilization	2	2	1	1	2
3. Photosynthetic efficiency	1	1	1	1	1
4. Rhizosphere effects	1	1	1	1	0
5. Basic stress physiology and genetics	1	1	1	1	0
E. PHYSICAL SOIL CONSTRAINTS					
1. Water management in rainfed system	1	3	2	0	3
2. Erosion prevention and control	2	3	2	0	3
3. Mechanical impedance	2	3	1	0	2
4. Land clearing methods	3	1	1	0	2

Table 7 (Continued).

Research and Development Components	Humid Tropics	Semiarid Tropics	Acid Savannas	Wetlands	Steeplands
F. IMPROVED FARMING SYSTEMS					
1. Sustained production in Oxisols/Ultisols	3	0	3	0	0
2. Multiple cropping	2	2	1	1	3
3. Agroforestry	3	3	1	0	3
4. Intensive fertilization of high value crops	0	0	0	0	0
5. Management of irrigated farming systems	0	1	0	0	1
6. Low input farming systems	3	3	3	3	3
G. TECHNOLOGY TRANSFER					
1. Validation and adaptation of research results	3	3	3	3	3
2. Training	3	3	3	2	3
3. Developing fertilizer recommendations	3	2	3	2	2
4. Information services	3	3	3	3	3

12. Low fertilizer input farming systems
13. Technology validation and adaptation
14. Training
15. Developing fertilizer recommendations
16. Information services

In addition, research topics of medium priority include fertilizer marketing and manufacturing technology, potassium and nutrient balance, sulfur,and micronutrients, use of organic residues, erosion control, mechanical impedance and multiple cropping. The preponderance of chemical rather than physical priorities reflect the acid, infertile nature of these soils.

Table 8 indicates the projected efforts of these and other research components and Table 9 summarizes the framework for the humid tropics. The following summary is adapted from Bentley (1980): Achievements applicable to food production on farms during the next ten years are expected to be moderate due to the magnitude and complexity of this enormous task. Successful farming systems, however, are expected to have a large impact in the 1990's and beyond. The cost of an integrated research program is large, particularly because of the logistical problems involved. The ease of transfer of a successful technology, once it is practically developed, is high. The expected long-term payoff is expected to be very high, since this program is the cornerstone for developing new lands for cultivation in the tropics--and for preventing resource and environmental damages which, in light of current knowledge and capabilities, should not be permitted to occur.

D. The Semiarid Tropics

The semiarid tropics are characterized by a protracted dry season of six to nine months duration. This ecological zone totals about 2100 million hectares in Africa, Asia and the Americas (Figure 1) and more than 550 million people live in such areas (Kampen and Burford, 1980). Many of them however, depend on irrigated areas for their food supplies. Because of the generally inadequate rainfall, its erratic distribution and highly variable amount, the reliability and levels of crop yields are exceedingly uncertain in such regions. A large proportion of the people in the semiarid areas of the tropics have a very precarious and uncertain life. The hazards of drought and of occasional intense rainstorms are frequently very damaging.

Because of the exceedingly variable precipitation and growing conditions, agricultural research in rainfed semiarid tropical areas with crops is especially difficult and has traditionally been meager in relation to the land area, numbers of people and agricultural production. Irrigation, where practical, is practiced extensively in India, but is frequently affected by secondary salinity and drainage problems as well as by uncertainties and variations in water supply. There has therefore, been a scarcity of improved agricultural methods arising from the research for rainfed lands. It is, therefore, understandable that yields in the semiarid tropics have been rather static, even declining in some areas, due to impairment of land under the farming systems and practices being employed.

Table 8. Expected short and long term impact, relative magnitude of costs, ease of transfer and existing capabilities for research components in the relevant agroecological zones that rank high or medium priority (1 = low; 2 = medium; 3 = high).

Research Component	Relevant agroecological zone					Impact over		Magnitude of cost	Ease of transfer	Pay-off	Existing capability
	HT	SAT	AS	WL	STP	Short term	Long term				
RESOURCE APPRAISAL											
Soil characterization	X	X	X	X	X	1	2	2	2	3	2
Classification for plant nutrition	X	X	X	X	X	2	3	2	2	3	1
Fertility evaluation	X	X	X	X	X	2	3	2	3	3	2
Fertilizer marketing and use	X	X	X	X	X	2	2	1	2	2	1
Fertilizer manufacturing tech.	X		X	X		1	3	2	1	2	1
STRESS FACTORS											
Selecting tolerant germplasm	X	X	X	X	X	2	3	3	3	3	1
Management of soil acidity	X		X			2	3	2	2	3	2
Salinity		X		X		1	1	3	1	1	2
NUTRITIONAL CONSTRAINTS											
N fertilizer efficiency	X		X	X		3	3	1	3	3	2
P fertilizer efficiency	X		X		X	2	3	2	3	3	2
K and nutrient balance	X		X			1	3	1	2	3	1
Sulfur	X		X	X	X	2	3	2	3	3	1
Micronutrients	X		X	X	X	2	3	2	3	3	1
BIOLOGICAL CONSTRAINTS											
Biological N fixation	X	X	X	X	X	1	3	1	2	3	2
Organic residue utilization	X	X			X	1	2	2	2	2	1
PHYSICAL CONSTRAINTS											
Water mgmt. in rainfed system		X	X		X	1	2	1	2	2	1
Erosion prevention and control	X	X	X		X	1	2	1	2	2	1
Mechanical impedance	X	X			X	1	2	1	2	2	1
Land clearing	X				X	2	3	2	3	3	1

Table 8 (Continued).

Research Component	Relevant agroecological zone HT	SAT	AS	WL	STP	Impact over Short term	Long term	Magnitude of cost	Ease of transfer	Pay-off	Existing capability
IMPROVED FARMING SYSTEMS											
Sustained prod. in Oxisols/Ult.	X		X			2	3	3	3	3	1
Multiple cropping	X	X			X	2	2	2	2	2	2
Agroforestry	X	X			X	1	2	2	2	2	1
Low input systems	X	X	X	X	X	2	3	2	3	3	1
TECHNOLOGY TRANSFER											
Validation/adaptation of research	X	X	X	X	X	3	3	3		3	1
Training	X	X	X	X	X	2	3	2	3	3	1
Fertilization recommendations	X	X	X	X	X	2	3	2	2	3	2
Information services	X	X	X	X	X	2	2	2	3	3	1

Adapted from the Bonn Soils Panel draft report for 15 components. The rest provided by the authors.

Table 9. Expected short and long term impact, relative magnitude of cost, ease of transfer and existing capabilities for priority research by agroecological zone (1 = low; 2 = moderate; 3 = high).

Agroecological Zone	Impact Short term	Impact Long term	Magnitude of cost	Ease of Transfer	Pay off	Existing capability
Humid tropics	2	3	3	3	3	1
Semiarid tropics	2	3	2	3	3	2
Acid savannas	3	3	2	3	3	2
Wetlands	2	3	2	2	3	2
Steeplands	1	3	3	2	3	1

Adapted and expanded from the Bonn Conference Soil Panels draft report (unpublished).

Soil-plant nutrition problems that adversely affect the level and stability of food production in rainfed semiarid tropical areas are both physical and chemical, but in contrast with the humid tropics the physical constraints are more critical. Lack of sufficient soil moisture and surface crusting severely affect food production on vast areas of semiarid soils. Brief, intense rainfall frequently causes turbulent runoff with loss of valuable moisture, as well as soil erosion, siltation and flooding. Sometimes intense rainstorms cause damaging flooding in parts of fields. Because of sparse growth and the large numbers of animals, there is usually a general lack of crop residues, vegetative cover and mulch materials for soil protection. Some residues and much dung are burned for cooking. Consequently, when intense rains occur, runoff, erosion and crusting of bare soils are important problems.

Table 7 identifies 12 research components considered of high priority for the semiarid tropics:

1. Soil characterization and classification
2. Classification for plant nutrition
3. Soil fertility evaluation
4. Biological N fixation
5. Water management in rainfed systems, including water harvesting
6. Erosion prevention and control
7. Mechanical impedance (principally surface crusting or capping)
8. Agroforestry (including both pastures and trees)
9. Low input farming systems
10. Validation and adaptation of research results
11. Training
12. Information services

In addition, the following research components were considered of medium priority: Fertilizer marketing, selection of germplasm tolerant to soil stress, salinity, organic residue utilization, multiple cropping and developing fertilizer recommendations.

Table 9 indicates that short-term results of soil and water research for the semiarid tropics are expected to be moderately good and that long-term prospects will be high. Anticipated costs of needed research are moderate and ease of transfer of proven technology is expected to be high. Results in terms of increased yields should be high. The capability of national institutes to do the needed research is moderately good if there is adequate support and encouragement from both internal and external sources. Considerable capability gaps exist between the semiarid tropics of Asia as compared to those of Africa and Latin America.

E. The Acid Savannas

This agroecological zone composes the portion of the tropics with a strong dry season of four to six months duration, savanna vegetation and predominantly acid soils of the orders Oxisol and Ultisol. Figure 1 shows that the main extensions are in tropical America, particularly the Cerrado of Brazil and the Llanos of Colombia and Venezuela. Acid savanna regions also occur in Central

Africa and Southeast Asia. The vast areas of acid savannas, along with the humid tropics is where agricultural land expansion during the next 20 years is expected to occur (FAO, 1979b). Because of less infrastructure problems the acid savannas of tropical America are being developed at a faster rate than the humid tropics. Cattle production systems are the principal activity but annual crop and crop/pasture successions are becoming increasingly important as the population frontier moves inland. Recent reviews by Sanchez and Tergas (1979) and Marchetti and Machado (1980) summarize ongoing research. This rapid development is often not accompanied by proper soil and plant nutrition technology which frequently results in crop failures, poor pasture persistence and soil erosion.

Table 7 identifies 15 research components considered of high priority for the acid savannas:

1. Soil characterization and classification
2. Soil classification for plant nutrition
3. Soil fertility evaluation
4. Selecting germplasm tolerant to soil stress
5. Management of soil acidity
6. Phosphorus fertilizer management
7. Sulfur
8. Micronutrients
9. Biological N fixation
10. Sustained production in Oxisols/Ultisols
11. Low input farming systems (both crops and pastures)
12. Validation and adaptation of research results
13. Training
14. Developing fertilizer recommendations
15. Information services

Moderately high research priorities also include fertilizer marketing, fertilizer manufacturing technology (particularly rock phosphate modifications), N fertilizer efficiency, potassium and nutrient balance, water management in rainfed systems, and erosion prevention and control.

The acid savannas combine the fertility limitations of the humid tropics with a moisture stress of less intensity than in the semiarid tropics. The interaction of both factors as well as socioeconomic ones generally show more promise of rapid success in the acid savannas than in the other two agroecological zones. Table 9 therefore, shows a high expected impact on both short- and long-term, a moderate magnitude of cost, high ease of transfer and moderate existing institutional capabilities.

F. The Wetlands

The wetlands compose that part of the tropics with poor drainage and/or devoted to flooded rice cultivation. The great majority of rice farmers, 90% of whom live in the wetlands of Asia, cultivate farms of less than three hectares. There is little land that can be brought under rice cultivation that does not have severe soil constraints (IRRI, 1980). Thus, to increase food production in the wetlands it is necessary to increase the yields of rice and other crops grown in these small farms, increase the number of crops taken each year or solve constraints on the marginal soils. In Africa and Latin America, there is considerable potential for expanding rice cultivation in underutilized wetlands (Moormann and Greenland, 1980).

In the past, most attention has been given to increasing the yields per hectare, and work on this aspect must continue. However, another avenue to increased production, increasing the number of crops grown each year, has been inadequately developed and offers the advantage that the risk factor in relation to production inputs is usually less. Furthermore, this avenue to additional production often increases the period of time per year over which the farmer and his family are gainfully employed. Moreover, the need for external inputs such as to increase total production per year is less than would be required if the same increase were obtained by boosting yields per crop.

Diversified research and experimentation are needed to increase food production from ricelands. Cropping systems are highly environment specific. Thus, if studies on cropping systems are to be widely applicable to small farmers throughout Asia and other parts of the world, research has to be done on a wide range of sites, and mainly at farmer fields. Considerable progress has already been made in relation to the dry seeding of rice to ensure that rice will germinate with the initial rains and mature at the earliest possible date. Substantial improvements have also been made in the yield potential and length of time required for new rice varieties to attain maturity. Another important factor is the selection of rice varieties which enable a ratoon crop to be obtained. The production of a ratoon crop involves a minimum of inputs and will often result in additional yields of 1 to 2 tons per hectare.

Table 7 identifies eight high priority research components for the wetlands:

1. Soil characterization and classification, particularly to properly characterize farming systems research sites.
2. Soil classification for plant nutrition constraints.
3. Selection of germplasm tolerant to soil stress.
4. Nitrogen fertilizer efficiency.
5. Biological N fixation.
6. Low input farming systems (emphasis on rainfed lowland and upland rice).
7. Technology validation and adaptation of research results.
8. Information servies.

In addition, other important medium priority considerations include soil fertility evaluation, fertilizer marketing, fertilizer manufacturing technology (primarily slow release N sources), management of coastal saline soils, sulfur, micronutrients, training and developing fertilizer recommendations.

Plant nutrition research in the wetlands is somewhat more advanced than in other agroecological zones, but the work on rice-based cropping systems in marginal soils is poorly developed. Table 9 shows that short-term impact is expected to be moderate but the long-term impact will be high, the magnitude of the cost moderate, the ease of transfer moderate and, the existing capability moderate but the payoff high. These considerations must be weighed in relation to the overwhelming importance of rice production in feeding the world's poor.

G. The Steeplands

Large areas of densely populated regions of the tropics and subtropics occur on hilly terrain where population pressures are causing erosion to be a major concern. Farmers originally settled in these areas because of a generally high native fertility status, and a more favorable climate than the adjacent lowlands. Population growth has fragmented the land in many small patches and farmers often carry crop intensification too far, resulting in widespread soil erosion. Often the more fertile alluvial valleys are under the control of large landowners or other kinds of farm enterprises, while the small farmers are stuck with the steep areas. Examples of the steeplands are found throughout the Andean chain from Mexico to Bolivia, in parts of the Caribbean, the mountainous areas of tropical Africa, the Himalayan foothills, the hill country of Southeast Asia and adjacent islands not devoted to terraced irrigated rice production. Figure 1 shows some of the main locations.

Table 7 identifies 12 research components as top priority for the steeplands:

1. Soil characterization and classification
2. Classification for plant nutrition
3. Soil fertility evaluation
4. Biological N fixation
5. Water management in rainfed systems
6. Erosion prevention and control (the overriding concern)
7. Multiple cropping (aiming at year-round soil cover)
8. Agroforestry
9. Low input farming systems
10. Validation and adaptation of research results
11. Training
12. Information services

In addition, fertilizer marketing, germplasm tolerance to soil stresses, phosphorus fertilizer management, sulfur, micronutrients, organic residue utilization, mechanical impedance, land clearing methods and developing fertilizer recommendations are areas of medium priority.

Unlike the other zones where systematic efforts are being made to alleviate soil and plant nutrition constraints, no such approach has been focused on steepland areas. There is also no recognized center of excellence for soil-plant nutrition research in this agroecological zone. In addition, the operational aspects of carrying out the proposed research are quite complicated and costly. Effective solutions have to involve watershed studies, including both erosional and depositional landscape positions. Civil engineering and socioeconomic considerations weigh heavily.

All these considerations indicate a low probability of impact in the short run but a high impact in the long term. The magnitude of the cost is high because of the watershed dimensions and the extreme variability in soils and microclimates encountered in steepland regions. The ease of transfer is moderate, again because of the variability. The payoff however, is envisioned as high, perhaps not in terms of making large contributions to world food production but in preventing the deterioration of the land resource base and subsequent social upheavals. The low rating for existing capabilities underscores the necessity for training and developing research programs with the components that have been outlined.

H. General Considerations

The preceeding sections show some research components that rate either high or medium priority for all agroecological zones. Table 8 shows that these 10 components are also considered to have high possibility of payoff. The 10 components relate primarily to resource appraisal aspects (soil characterization, classification for plant nutrition, soil fertility evaluation) and technology transfer (validation, training, fertilizer recommendations and information services). Only selecting plants for soil stress tolerance and biological N fixation fit outside of these aspects. These components are probably very important in the remaining agroecological zones of the developing world as well. Consequently, efforts in these aspects as suggested in this report could also benefit other agroecological zones.

Tables 7, 8 and 9 also show that several research components do not rate high in the context of an agroecological zone approach; examples are photosynthetic efficiency, rhizosphere effects and basic aspects of stress physiology and genetics. These components were identified by the earlier studies which had more influence from scientists based in the developed countries. The FAO, Soil Constraints, North Carolina and Bonn studies were focused towards the developing countries as opposed to the first three which had a worldwide focus. The writers of this report acknowledge the importance and potential contribution of these issues but are of the opinion that the main responsibility for carrying them out resides in the more sophisticated research laboratories of the world.

VII. PRESENT RESEARCH INVOLVEMENT

Various institutions have major involvement in plant nutrition research in developing countries. Table 10 attempts to summarize the magnitude of involvement. With few exceptions, most portions of the major research components cited in the previous chapter are being addressed by IARCs, other international institutes, developed country institutions and national research systems. It is not within the purview of this chapter to detail what is being done in each of the major research areas by all involved national, bilateral and international organizations. If this were attempted, most likely some important contributors would be inadvertently omitted. Rather, this chapter will briefly review the major soil-plant nutrition research activities of selected IARCs, other selected international organizations, developed country institutes and national institutions as examples of ongoing work. Linkages with other institutes, although implicit, are not mentioned.

A. CGIAR System

1. IRRI. IRRI has major involvement in the chemistry of flooded rice soils, plant nutrition-soil fertility aspects of rice production, evaluating rice tolerance to adverse soil conditions, increasing N fertilizer efficiencies through the INSFERR network, intensifying cropping in upland and rainfed areas via multiple cropping, evaluating biolotical N fixation by *Azolla* for rice production, validation/adaptation of research, degree and non-degree training in soil-plant nutrition as related to rice.

2. CIAT. The objective of CIAT activities has centered on tropical pastures, beans and cassava, and rice, primarily in Latin America. Emphasis is given to acid savannas and steepland areas. A factor-oriented program, land resource evaluation cuts across commodity lines. CIAT's major involvement in plant nutrition-related research activities includes land resource evaluation, selecting germplasm tolerance to acid soil stresses, management of soil acidity, improving P fertilizer efficiency, symbiotic biological N fixation, sustained production in Oxisols/Ultisols, low input systems, validation/adaptation of research, and non-degree and degree training.

3. IITA. In order to address its primary objective of improving the quality and quantity of food crops in the lowland humid tropics, IITA has major research activities on soil characterization, selecting tolerant germplasm of cassava, yams, grain legumes and cereal grains, erosion prevention and control, mechanical impedance, land clearing, sustained production in Oxisols/Ultisols, multiple cropping, validation/adaptation of research, and non-degree and degree training. BNF is also addressed. IITA's research concentrates in Africa.

4. ICRISAT. The mandate of ICRISAT is to improve farming systems and water management in the semiarid tropics. It also has primary responsibility for sorghum, pearl millet, pigeon peas, chickpeas and groundnuts. Its major involvement in soil-plant nutrition related research includes selecting tolerant germplasm, biological nitrogen fixation, water management in rainfed systems, mechanical impedance, multiple cropping, validation/adaptation of research, and non-degree and degree training. It is also involved in soil characterization.

Table 10. Current major soil-plant nutrition research involvement in developing countries by kinds of institutions.*

Research and Development Components	CGIAR System	Other Int'l Institutes	Developed Country Institutes	National Research Institutes: Asia	Latin America	Africa
A. RESOURCE APPRAISAL						
1. Soil characterization and classification	2	4	3	2	3	3
2. Soil classification for plant nutrition	1	2	4	1	1	0
3. Soil fertility evaluation	2	3	4	2	3	1
4. Fertilizer supplies, price, distribution and use	4	5	3	3	3	3
5. Fertilizer manufacturing technology	0	5	0	2	2	1
B. STRESS FACTORS						
1. Selection of germplasm tolerant to soil stresses	3	2	4	3	3	1
2. Management of soil acidity	4	2	4	1	3	1
3. Salinity	2	3	3	3	3	3
C. NUTRITIONAL CONSTRAINTS						
1. Nitrogen fertilizer efficiency	5	5	4	4	3	3
2. Phosphorus fertilizer management	4	4	4	3	4	2
3. Potassium and nutrient balance	3	3	3	2	2	1
4. Sulfur	2	3	3	3	3	2
5. Micronutrients	2	3	3	3	3	2
D. BIOLOGICAL CONSTRAINTS						
1. Biological nitrogen fixation (BNF)	5	0	5	4	4	1
2. Organic residue utilization	2	2	1	4	1	2
3. Photosynthetic efficiency	1	1	4	0	0	0
4. Rhizosphere effects	2	0	3	0	0	0
5. Basic stress physiology and genetics	4	0	5	1	1	0

Table 10 (Continued).

Research and Development Components	CGIAR System	Other Int'l Institutes	Developed Country Institutes	National Research Institutes Asia	Latin America	Africa
E. PHYSICAL SOIL CONSTRAINTS						
1. Water management in rainfed systems	5	1	1	3	3	3
2. Erosion prevention and control	4	2	2	3	3	3
3. Mechanical impedance	4	2	3	2	2	3
4. Land clearing methods	4	0	4	1	3	1
F. IMPROVED FARMING SYSTEMS						
1. Sustained production in Oxisols/Ultisols	4	2	5	1	3	0
2. Multiple cropping	4	2	3	3	3	3
3. Agroforestry	1	2	2	1	1	1
4. Intensive fertilization of high value crops	2	1	2	3	3	3
5. Management of irrigated farming systems in arid areas	1	2	2	3	3	1
6. Low fertilizer input farming systems	2	1	4	3	3	3
G. TECHNOLOGY TRANSFER						
1. Validation and adaptation of research results	4	3	3	2	2	1
2. Training	4	4	4	3	3	2
3. Developing fertilizer recommendations	3	4	4	3	3	3
4. Information services	4	4	3	2	2	1

*0 - None; 1 - Scattered or rudimentary efforts; 2 - Initial or systematic efforts by one or few institutions; 3 - Widespread efforts by several institutions; 4 - One or few recognized leading institutions; 5 - Center of excellence and established network.

5. CIMMYT. In fulfilling its mandate to improve maize and wheat production in developing countries, CIMMYT has centered more on breeding than on soil-plant nutrition research. However, its breeding programs have included adaptation to drought and other stresses. Recently, CIMMYT is attempting to incorporate dwarfing genes in Al-tolerant wheat varieties from Brazil. It has also given top priority in its current wheat program to improved agronomic practices. Structural cnanges in the maize plant has enabled it to make more efficient use of soil nutrient and solar energy.

6. CIP. To improve potatoes in developing countries, CIP has centered on plant breeding and control of diseases and insect pests. CIP's soil-plant nutrition-related research focuses on selecting germplasm more widely adapted to environmental stress, including for the humid tropics, and on training. Unlike the four previous centers, soil and plant nutrition research is not a major part of CIP's core program.

7. ILCA. The goal of ILCA is to increase animal output through improved production and range management systems. Improved farming systems are a major component of ILCA's research activities. Little work in plant nutrition is in progress.

8. ICARDA. ICARDA's mission is to help increase and stabilize food production in the developing countries of the temperate zone with arid or semiarid climates. Its farming systems work is of relevance to soil-plant nutrition research, as well as the biological nitrogen fixation component of its lentil and broad bean programs. The soil, water and nutrient (SWAN) project of ICARDA is investigating moisture and nutrient interactions in xeric environments.

9. IFPRI. In making projections related to food production and needs of developing countries, IFPRI's fertilizer marketing projections are of relevance to soil-plant nutrition research.

10. WARDA. As part of its mandate to foster rice production in West Africa, WARDS is involved in soil fertility work.

Plant nutrition research is not included in the activities of the three remaining CGIAR centers, ILRAD, IBPGR and ISNAR.

B. Other International Organizations

Although many organizations other than those following are involved in some plant nutrition research activities, those listed were chosen for their overall pertinence to this study. Recognized also are many funding agencies, such as World Bank, UNDP, the regional banks and the foundations, which support soil-plant nutrition research executed by other organizations; however, these funding groups are not covered as the discussion centers on those performing the work.

1. FAO. The World Soils Map attests FAO's importance and impact in soil characterization. Other major relevant involvements by FAO are: Land resource evaluation through agroecological zones, validation/adaptation of research, training, fertilizer recommendations and information services, including CARIS.

FAO also is involved with monitoring fertilizer demand and supply projections and utilization of organic residues. FAO has been fostering salinity research. It cooperates with all relevant IARCs, numerous developed country institutes of virtually every national government of developing countries.

2. IFDC. The mission of IFDC is to develop appropriate fertilizer technology and relate know-how to sustain and increase food production in the developing countries. In fulfilling that mission, IFDC's activities pertinent to this study are fertilizer manufacturing technology, fertilizer marketing and use, N fertilizer efficiency, P fertilizer efficiency, validation/adaptation of research, and non-degree and degree training. Agronomic research operations in developing countries are carried primarily through IARCs. More details on IFDC are given in the following chapter.

3. AVRDC. In its vegetable production research, AVRDC is involved with selecting germplasm tolerant to adverse soil conditions. Training is an important component of its programs.

4. ICRAF. The agroforestry and low input systems work fostered by ICRAF have particular relevance to research needs identified by the current study. Cooperative work with various international, regional, developed country and national institutions is envisioned.

5. IICA. This organization attempts to catalyze agricultural research activities in Latin America. Included in these are soil characterization, NPK fertilizer research, erosion prevention and control, validation/adaptation of research, and training. Cooperation is with FAO, developed country institutes, international centers and virtually all national research institutions in Latin America.

6. CATIE. The most relevant research work of Central American-based CATIE to soil-plant nutrition is its intensive multiple cropping program. Also relevant would be its non-degree and degree training program. Cooperation is with several international, developed country and national institutions.

7. ACSAD. The Arab Center for Semi-Arid Lands and Drylands cooperates closely with ICARDA's food production and farming systems research in arid and semi-arid climates.

C. Developed Country Institutes

1. Western European institutions. The main participants in the United Kingdom include the Universities of Reading, Leeds, Bristol and Nottingham, the Rothamsted Experiment Station, the Leadcombe Laboratories and the Land Resource Development Center (LRDC) of the Overseas Development Ministry. The latter has played a major role in conducting soil surveys in developing countries. In France, ORSTOM and IRAT have conducted for several decades research in almost all aspects of soil-plant nutrition mentioned in this report, primarily in Francophone, Africa. The Agricultural University at Wageningen, the International Soils Museum, Royal Tropical Institute, International Institute for Land Reclamation and Improvement, and Utrecht University represent the

major portion of the Dutch involvement. Ghent University of Belgium is active in tropical soil characterization and mineral nutrition research. Many West German universities are involved in bilateral programs mostly supported by the German Agency for Technical Cooperation (GTZ). The Butenhof Research Station of Kali und Saltz is specifically involved in potassium and nutrient balance research in developing countries. Several Scandinavian universities supported by their national development assistance agencies are increasingly involved in bilateral technical assistance that includes research on plant nutrition. Most of the above institutions are involved in validation/adaptation of research, training, both non-degree and degree--many with fertilizer recommendations. These groups cooperate among themselves with various international, regional, other developed country and national institutions.

Also of relevance are the institutes dedicated to the study of a particular element. These include the Center for Nitrogen Study in Geneva, IMPHOS (Institute Mondial du Phosphore in Paris, IPI (International Potash Institute) in Berne, and the Sulfur Institute in London. Research on the efficiencies of these particular elements is conducted and funded by these institutes often in cooperation with other groups having similar goals.

2. Pacific institutions. In Japan, Kyoto and Hokkaido Universities have been particularly active in soil and plant nutrition research, primarily in relation to Southeast Asian rice producing regions. CSIRO and several Australian Universities are showing increasing involvement in soil and nutrition research in developing countries with emphasis on tropical pasture production, phosphorus nutrition and soil characterization. The New Zealand Bureau of Soils along with several universities are also heavily involved in plant nutrition research with emphasis on volcanic regions and the South Pacific islands.

3. North American institutions. Most major U. S. land grant universities are involved in soil-plant nutrition research in the tropics and are therefore, too numerous to cite. At present, three major research efforts financed by USAID are executed by Cornell University, the University of Hawaii, North Carolina State University, Texas A & M University and the Soil Conservation Service of USDA. The Title XII-sponsored Soil Management Collaborative Research Support Program involves long-term soil management research in the humid tropics of Peru and Indonesia (North Carolina State and Hawaii), the semiarid tropics of West Africa (Texas A & M) and the acid savannas of Brazil (Cornell-North Carolina State), in collaboration with several national institutions and international centers. Major pertinent activities are soil characterization, soil classification for plant nutrition, fertility evaluation, selecting tolerant germplasm, management of soil acidity, N and P fertilizer efficiencies, BNF, organic residue utilization, mechanical impedance, land clearing, sustained production in Oxisols/Ultisols, multiple cropping, agroforestry, low input systems, validation/adaptation of research, and training.

Another USAID-financed program relevant to this study is the Soil Management Support Services. It is contracted through the Soil Conservation Service of USDA and provides short-term services upon request to national institutions.

Research activities are related to soil characterization, particularly the internationalization of Soil Taxonomy. The Benchmark Soils Project conducted by the Universities of Hawaii and Puerto Rico conduct research on how to match soil properties with plant response.

Other U. S. universities such as Purdue, Wisconsin, Ohio State, Prairie View, Kentucky, Florida, Minnesota and California (Davis and Riverside) are also involved in soil-plant nutrition research in developing countries.

Various Canadian research activities related to soil-plant nutrition are underway in developing countries. Many of those activities are financed by IDRC and CIDA and are carried out by both that agency and contracting Canadian universities. Collaboration is with IARCs, some developed country institutions and various national institutions.

D. National Research Systems

Though near impossible to be all inclusive, pertinent institutional research activities related to soil-plant nutrition will be addressed by region. Many national research institutions are quite strong, among which are some in India, Indonesia, Malaysia and Brazil. Established commodity institutions working on cash crops have done considerable work in soil-plant nutrition.

1. Asia. Many Asian countries have national institutions which perform research in soil characterization and few are involved in fertility evaluation, soil classification for plant nutrition; several conduct fertilizer marketing and use and fertilizer manufacturing technology research. Some are involved with research for selecting tolerant germplasm. Many are researching increased efficiencies of fertilizers, especially N and P. China is involved in both *Azolla* research for BNF and organic residues utilization; India has some research efforts in the latter. Some Asian countries are researching water management of rainfed systems and multiple cropping. Many conduct validation/adaptation research, are involved in training and most make some approach at researching fertilizer recommendations. Cooperation exists with IRRI, ICRISAT, CIMMYT, CIP, FAO, IFDC, AVRDC and several developed country institutions.

2. Latin America. Most Latin American countries have national institutions involved in soil characterization research, several with fertility evaluation. Virtually all have some type of research on nutritional constraints, especially related to N and P. To the authors' knowledge, only Brazil has an active research program to select varieties tolerant to adverse soil conditions. Several, including Brazil and Peru, are researching soil acidity management. Brazil is also researching non-symbiotic N fixation and land clearing. Several are involved in water management research in rainfed systems, some with erosion control, and many with validation/adaptation of research, training and fertilizer recommendation research. Cooperation is with CIAT, IRRI, FAO, IICA, CATIE, CIP, IFDC and several developed country institutions, including the U. S. universities.

3. Africa. Several African countries have soil characterization research programs, but few research any of the other resource appraisal components. A few are conducting salinity research. Many are conducting NPK fertilizer trials in an effort to demonstrate the value of fertilizers. Some are researching water

management in rainfed systems, erosion prevention and control and mechanical impedance. Improved farming systems are researched by a few. Several are involved in validation/adaptation of research; many with training and a few with fertilizer recommendation research. Collaborative work is with IITA, WARDA, ICRISAT, IRRI, FAO, many European institutions and several other developed country institutions.

E. General Remarks

From this rather broad brush stroke summarization of current research efforts related to soil-plant nutrition by institutions within the CGIAR system, other international, developed country and national institutions, one is impressed by the fact that, although some gaps certainly exist, soil-plant nutrition research is not neglected.

Just as striking is the impression that while many research efforts in soil-plant nutrition are being made, they are not conducted in a sufficiently coordinated manner. For instance, inorganic fertilizer trials are conducted in virtually every country of the world; but how coordinated are these? Are the results correlated with soil test values to improve fertilizer recommendations? Are the results accessible to neighboring countries or other countries in a similar agroecological zone? Similar questions can be asked of other soil-plant nutrition research, whether much or little research is conducted in that particular component.

VIII. THE INTERNATIONAL FERTILIZER DEVELOPMENT CENTER

Although the International Fertilizer Development Center (IFDC) was mentioned in the previous chapter, more detail on its activities relevant to plant nutrition is herein supplied. Such treatment is proper and fitting as a primary impetus for conducting the Plant Nutrition Study was the deliberation by TAC and CGIAR on a 1979 proposal from the United States to include IFDC within the IARC's receiving direct support from the CGIAR. In response to that proposal, a TAC team visited IFDC and reported its recommendations (TAC, 1979b) to the CGIAR. In considering the TAC report and the IFDC issue, the CGIAR (1980b) felt a need for further assessment of the factor-oriented area of plant nutrition. Hence, in May 1980 the authors were asked by TAC to undertake this study, including the role of IFDC. In November 1980 the authors visited IFDC. The following information is based on information gathered during that visit and since.

The development and transfer of appropriate fertilizer technology to increase and sustain food production in the developing world is the mission of IFDC. In fulfilling that mission, IFDC's activities relevant to this study are improving N and P fertilizer utilization efficiencies in developing countries, developing fertilizer manufacturing technology appropriate for developing countries, monitoring fertilizer marketing and use in developing countries, adapting research findings in developing countries, and training of developing country nationals. This role is unique among institutions devoted to improving plant nutrition efficiency in the developing world. A description of the main activities follows.

A. Improving Nitrogen and Phosphorus Fertilizer Utilization Efficiencies.

This major thrust of IFDC is centered in two areas: flooded rice soils and upland soils. Nitrogen is the most energy consuming plant nutrient to produce, requiring 50×10^6 Kcal energy/ton N. Improvements in efficiency of N fertilizer utilization would have a substantial impact on the amount of fertilizer N production required.

1. Nitrogen in Flooded Rice. Nearly 60% of the N used in the developing countries is for flooded rice. Urea is the main source of N used for that crop. Yet only 20-33% of the urea applied by traditional methods to flooded rice actually gets into the plant. Thus, at best, only one of every three bags of urea are utilized.

Work by the IFDC in increasing the efficiency of N fertilizer applied to flooded rice is, in the opinion of the authors, second to none worldwide. In 1977, IFDC researchers began investigating the actual fate of N applied to flooded rice by traditional methods at IRRI. They and others found the reasons for the low N efficiency in flooded rice to be volatilization (accounting for up to 60% loss from broadcast urea), denitrification and leaching.

By point placement of the Scandanavian-developed urea supergranule (USG) to minimize N losses, IFDC researchers have increased applied N recovery to 80% in some trials. This work was validated on 235 farmer's fields in 16 countries in cooperation with IRRI's INSFFER and the INPUT program and on 322 trials on experiment stations in India and in cooperation with ICRISAT during 1979 and

and in the Philippines in 1980. The researchers also found that while urea applications reduce growth of blue-green algae, deep placement of the USG did not reduce the growth of these N-fixing organisms nearly as much as the traditionally split broadcast applied urea. The IFDC is investigating how site characteristics affect rice respnse to N source placement.

A tentative prescription for the ideal N fertilizer for flooded rice has been developed by IFDC researchers:

1. Releases 10% of N within first 2 weeks of rice growth;
2. Releases the remainder linearly up to following 8 weeks;
3. Maintains 10-15 ppm N in soil solution;
4. Limits N concentration in flood water;
5. Restricts N volatilization in soil-fertilizer reaction zone;
6. Permits maximum BNF, especially that by blue-green algae.

This prescription now is being used by the Product Development Branch of IFDC to try to develop a N fertilizer with such properties.

2. Nitrogen in Upland Soils. This program which began in late 1979 has sequential priority emphasis in the semi-arid tropcs, the arid Mediterranean and the humid tropics. Research is based on present and future cropping systems of these areas as identified by collaboration with ICRISAT, ICARDA and, hopefully, IITA. Priorities include developing baseline N efficiency data, conducting N loss studies, developing and evaluating N sources, and modeling the fate of N in the various cropping systems. The latter is in collaboration with soil-plant-water modellers at Texas A & M's Blacklands Station. The overall IFDC approach is to determine causes of N inefficiency, estimated in the literature as being up to 50%, before trying to solve the problem. This approach proved successful in the flooded sites program and should also for this one.

3. Phosphorus Program. A second major thrust of IFDC's improved nutrient efficiency program addresses making better use of P resources in developing countries and determining better and less expensive sources of P for the developing countries. Two examples are provided.

One such effort, conducted collaboratively with CIAT and several agricultural research centers in tropical America, has as its objective a better utilization of indigenous resources in the developing countries of South America. Indigenous rock P resources are identified, characterized, including impurities, modified by several means and agronomically tested under greenhouse and field conditions. Modifications of the indigenous sources of rock P by fine grinding ($\leq$200 mesh), minigranulation ($\leq$50-200+), partial acidulation, thermal or chemical alteration are compared alone and in combination with triple superphosphate in various locations.

Direct application of some highly reactive rocks, such as the Sechura rock P from Peru (500 million ton deposit) have proven excellent for acid-tolerant pastures, as the acidity of the soil can be utilized to dissolve the rock P. Others with medium reactivity, such as the Huila (Colombia) and Olinda (Brazil), worked well with upland rice when finely ground (60-70%<200 mesh) and applied to the acid soils of Quilichao, Colombia. Minigranulation of rocks has been found to allow more uniform application of the rock P than does the traditional fine grinding. Partial acidulation has increased the reactivity of low reactivity rocks and has proven most effective on soils of high P retention and with crops with high internal P requirements. However, it is not necessary for high reactivity rocks. The degree of acidulation necessary for source-soil-crop combinations must be determined as must additional field validation with economic analyses. Mixtures of various rocks with simple and triple superphosphates are being evaluated to determine whether these can be effective P and S carriers and whether rock P dissolution is increased by the S. Long-term residual studies with these various P sources are being conducted.

Another IFDC effort deals specifically with Sri Lanka's Eppawala rock P deposit (25-50 million tons). This high grade deposit (36.4% P_2O_5) contains the minimum reserve required to make production economically possible. Characterization of the rock revealed, however, high Cl impurities of 10,500 ppm vs. normal of 500 ppm. Its reactivity is similar to that of Pesca (Colombia) rock P and much lower than Sechura or North Carolina rock P. Initial agronomic trials with this rock reflected its low reactivity. It does, however, represent an indigenous source, which through modification, can prove utilitarian for meeting the P needs of a developing country. More will be discussed under product development.

4. Training Program. The training component has evolved into a major activity of IFDC improved nutrient efficiency program. Examples include the 1978 IFDC/FERITT (Fertilizer Efficiency Research in the Tropics) Workshop at Ibadan for 25 participants from 14 countries, the 1979 IFDC/Indonesian Workshop for improved N, P, K, S efficiences in flooded rice and upland crops, the 1979 IFDC/IRRI (INSFFER) Workshop to strengthen theoretical and practical capabilities of 22 soil fertility cooperators in nine countries, the 1979 IFDC/Indian Workshop on fate and efficiency of urea-based fertilizers for rice, the 1979 IFDC Workshop on magnitude of N loss to train cooperators from three countries on lab and field methods of ^{15}N research, the 1980 IFDC/CIAT/FERITT Workshop on fertilizer efficiency in the tropics for 24 participants, the 1980 IFDC/FERITT/University of Nairobi/IITA Workshop on fertilizer efficiency research for 35 participants and the 1981 IFDC/FERITT/IITA Workshop on fertilizer efficiency research for 27 participants from 14 countires. Most of these workshops involve actual planting, management, harvesting, and evaluating field trials to determine fertilizer nutrient efficiences. Most, such as the 1981 workshop in Nigeria, are held in developing countries. Some, such as the IFDC/IRRI (INSFFER) Workshop, combine inorganic fertilizer management with BNF from *Azolla*. The ultimate goal of these workshops is to train host country counterparts that they may train other scientists and farmers to encourage early adoption of improved fertilizer materials and/or practices.

B. Product Development.

1. Nitrogen. Product development engineers are trying to make a N fertilizer fitted to the tentative prescription given by the agronomists for flooded rice. To obtain the appropriate N release rate by nitrogenous fertilizers, the engineers are trying various wax coatings in combination with urease and nitrification inhibitors. One of the most promising coatings appears to be rice bran wax (an extraction by-product from edible oil from rice bran) when combined with neem oil and a nitrification inhibitor. Some other work which has captured the attention of Korean counterparts is a double coating of urea with sodium silicate and a polycoat since rice has been known to respond to Si in some Korean soils.

This silica-polymer coated urea looks as good as SCU and USG in Philippine field trials.

Modification of urea by IFDC engineers without coatings or inhibitors also offers possible increases in efficiency. Nearly 90% of the urea used worldwide is prilled. A granular urea developed at IFDC results in less dust, a harder and larger particle which is smooth, easier to coat and thereby more effective for bulk blending. The urea super granules (1-3 g), briquettes (1-3 g) or tablets (up to 10 g) also can be easily made.

THE PUSRI pilot plant for pan granualtion of urea, the first in the developing world, was constructed in Indonesia under supervision of IFDC engineers. The process parameters for granulation were optimixed in this Indonesian government plant, PUSRI engineers were trained, and daily production capacity is 300 tons granular urea.

2. Phosphorus. This program is investigating various chemical and thermal methods which may be used to beneficially alter the characteristics of indigenous rock phosphates. Processes include partial acidulation, more complete acid alteration, the "clinker" process, utilization of waste P slimes normally discarded, thermal treatment of the rocks, and long-term interactions of microbes with rock P.

Pilot plants for the technology appropriate to the size of indigenous rock P sources near potential areas of food production can be designed and built in various landlocked developing countries. An example would be in Upper Volta which has small rock P deposits and an annual need for 5000 tons P_2O_5 for its food production. It currently pays $1000/ton P_2O_5, yet could furnish its own P needs with mini-scale technology. Estimated cost for a plant to produce 20,000-30,000 tons/year would be $5 million, the figure Upper Volta would pay to import 1/6 to 1/4 of that amount. Acid extraction of waste slimes such as those of Senegal, can recover 80% of the P which is normally lost in manufacturing P fertilizers from rock P.

The total P development project for indigenous rock P in Mali is an example of a combined product development/agronomic-economic evaluation project. Mali's P needs and costs are similar to those of Upper Volta. IFDC recently became involved in evaluating a potential partial acidualation plant for Mali's rock P. However, the study goes beyond mere product development as the product also will be evaluated for two years on 10 experiment stations in the country under sorghum, peanut, maize, cotton rotations and then for two more years at farm level. During the first two years soils are being characterized and socio-economic data are being collected for use in the latter two years of the study. Mali's Ministries of Mining and Agriculture are cooperating in the study. Collaboration with Texas A & M University's agricultural development project in Mali is being discussed.

3. Training program. The training of the engineers for the PUSRI urea pan granulation plant in Indonesia offers one example of a unique service provided by IFDC. Others include the 1979 IFDC/FERTIMEX Workshop for 20 participants on what a fertilizer man needs to know to run a fertilizer plant, the 52 participant IFDC Regional Fertilizer Granulation Workshop help in 1980 and in

Thailand for 42 participants from various countries, the 1981 IFDC management workshop for fertilizer plant maintenance and production for 33 participants from 11 countries, the 1981 IFDC blending and granulation seminar hosted in the Bahamas for 24 participants from 13 countries and the 1981 IFDC fertilizer production training program for 20 FERTIMEX engineers.

Another example is the IFDC/CEFER* training seminar for 30 Brazilian fertilizer industry specialists which gave not only a total of 219 training days in triple superphosphate production, pipe reactor granulation and monoammonium phosphate granulation using indigenous rocks, but also provided 40 days of technical assistance to the participants following course completion. Twenty-eight of these additional days were for pilot plant design and operation and went directly to CEFER. Also, IFDC hosted maintenance management training for 28 fertilizer producers from 13 countries in late 1980. IFDC training courses in Brazil were offered in 1981 to help assess pollution problems in fertilizer manufacturing in that country. No other international center has the mandate or capability to perform these tasks which are directly related to improved nutrient utilization efficiencies.

C. Monitoring Fertilizer Marketing and Distribution

IFDC monitors fertilizer marketing and distribution of these four major plant nutrients in developing countries in an effort to keep a pulse reading of the major needs and potential for filling these needs with developing country resources and capabilities. As an example of the benefit of such work is the 5-year roll forward supply/demand and marketing plan developed by Indonesia with IFDC backstopping. The benefits of such a plan are apparent and far-reaching.. For this plan, the Indonesians used IFDC as the model for establishing their fertilizer research unit.

The training component of IFDC's monitoring fertilizer marketing and distribution in developing countries is viewed as vital to the success of those activities. Both individual and group training is offered to maintain flexibility in meeting the individual needs of the developing countries. Participants trained by IFDC in fertilizer marketing and distribution has increased from 17 in 1977 to 71 in 1981.

Thirty-nine participants in 1980 were selected from 16 countries to participate in the 6-week course on fertilizer marketing and management. The participants supervise 590 persons in their jobs in the developing countries. Thus, a filter-down effect was possible from the course which was comprised of 4 weeks classroom work, a week visit to the Farmland Institute in Kansas and the University of Missouri, a three-day visit to Florida rock phosphate mines, fertilizer plants and ports and a two-day tour at TVA, a fertilizer equipment plant and a liquid fertilizer plant. Also included in the course was use of the Alpha Marketing Simulation in which the participants were divided in 10 "companies" and given hands-on experience through simulation variables in the system to make decisions on which would hinge the success or failure of marketing their fertilizer products. In addition, participants were trained in leadership effectiveness in order to improve the manager's efficiency in communication with his employees. That portion of the program was rated the highest of any by the participants.

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Regional marketing training programs are also important components. One such program began in India the week following the authors' 1980 visit to IFDC. Six IFDC staff participated in conducting this course. Marketing training courses implemented in 1981 included the IFDC regional marketing training program held in Thailand for 38 participants from 8 countries, the training program on international fertilizer marketing held in Saudi Arabia, and the fertilizer marketing and management training program just completed at IFDC for 27 participants from 13 countries. These marketing training programs are included in the unique purview of IFDC.

Often IFDC is asked to perform studies on fertilizer production, marketing, distribution, and use in developing countries. Requests for such services have been running at three to five per year for the last several years. Following are two examples.

IFDC conducted research in Bangladesh and India on farm level fertilizer economics to determine how rapidly improved production systems with fertilizers are adapted by farmers, to identify constraints and to ascertain policies needed to overcome them. In sampling 1053 farms in Bangladesh, IFDC found that 65% of the farmers used fertilizer during the rainy season, that 70% of the NPK consumed is by farmers with less than 2 hectares of land during the rainy season, and that those using fertilizer consider it part of a package, including high yielding varieties, pesticides, hired labor and other inputs.

Thailand asked IFDC to participate in evaluating its fertilizer production and marketing potential. Thailand currently uses 1 million tons of fertilizer annually but has no basic production facilities. Some granulation facilities are present. Diammonium phosphates and other ammonium fertilizers are imported. The study looked at demand through 1990 and projected that as early as 1987 Thailand could be using 1000 tons fertilizer daily produced by a recommended ammonium plant in-country. Piping offshore natural gas would supply the feedstock for the ammonium plant which would produce one half of its product as urea and the other as mono- or diammonium phosphates. Price analysis revealed little difference between importing phosphoric acid or using local rock phosphate sources in this production. The small guano deposits offer some potential for phosphate source. The fairly large KCl deposits as carnallite in NE Thailand also offer self-sufficiency potential. More fertilizer storage facilities away from Bangkok and near areas of production were recommended.

Similar studies were performed at the request of Indonesia, Nigeria, Colombia and Venezuela in 1981.

D. Additional Projected Thrusts

In addition to continuing to emphasize the activities detailed above, the IFDC looks toward increasing its efforts in improving sulfur fertilizer efficiencies, developing and evaluating new S products and monitoring marketing and distribution of S fertilizers in developing countries. IFDC's role on potassium, calcium and magnesium is presently under review. IFDC will continue to initiate granulation pilot plants with several other developing countries as these plants help to establish some self sufficiency in fertilizer production. Studies evaluating potential regional fertilizer production and distribution centers will be conducted. Training of developing country personnel in all areas detailed above will continue to receive emphasis.

E. Observations

The authors regard IFDC as an international center which uniquely fills a critical need in improving fertilizer utilization efficiencies for developing countries. No other international or national organization shares the mandate or performs a similar function. The IFDC's role in developing fertilizer manufacturing technology appropriate for developing countries is unquestionably unique. It has no vested profit motive, as do private companies, in developing either the mini- or large-scale technology for a single country or region. Its excellent staff and physical facilities provide the critical mass for technology development, followed by monitoring and backstopping these efforts. Its U.S. location is viewed as advantageous, rather than detrimental, because it takes advantage of the expertise of the adjacent facilities at TVA which has a similar mandate for developing improved fertilizer manufacturing technology for the U.S. The IFDC assistance in developing the PUSRI urea pan granulation plant in Indonesia, the first of its kind in the world, offers an example of how it fulfills its unique role.

Additionally, it is felt that the work of improved N utilization efficiency in flooded rice soils is making large gains due to the involvement of IFDC and its excellent scientific staff. The basic soil-plant nutrition research and the uniform production of the urea super granules and other N fertilizers at IFDC supporting the IFDC/IRRI (INSFFER) and IFDC/INPUT applied field research is resulting in major increases of N fertilizer utilization efficiency for flooded rice. When this technology is refined through further research and transferred to farmers' field, fewer new N fertilizer plants will be necessary.

The IFDC's unique monitoring of fertilizer marketing and distribution in developing countries allows these countries and others to look beyond the traditional supply and demand situation and to better address their capabilities, constraints and necessary actions to meet their fertilizer needs.

In summary, IFDC performs several functions unique among international centers, yet complementary to and supportive of the plant nutrition research conducted at CGIAR crop-oriented centers and elsewhere. In the fulfillment of its mission, IFDC has a well-defined and unique focus, excellent leadership and scientific staff who share a sense of urgency, quality research, good rapport with collaborating national and international institutions, and a fine mix of training with research.

IX. APPROACHES FOR TAC/CGIAR CONSIDERATION

This study has concentrated on technical aspects related to plant nutrition research without considering institutional aspects other than identifying some of the presently active institutions in Chapter VII and VIII. The next step is to address the question whether additional international action is needed and if so, whether it would be appropriate for consideration by the CGIAR system. Although the authors of this report are familiar with the history of TAC's deliberations related to this subject, including the TAC priorities paper (TAC, 1979a) they have deliberately carried their analysis up to this point independent from such considerations, relying rather on the major international studies devoted to assessing soil-plant nutrition research priorities. This chapter examines the findings documented in previous ones in terms of possible actions. The authors have used the TAC priorities paper (TAC, 1979a) as a basis for analysis, although recognizing that international initiatives are not necessarily limited to the CGIAR system.

A. General Considerations

Our analysis confirms the consensus of many TAC documents that plant nutrition research is not a neglected area. The considerable number of institutions involved in almost all priority research areas shows the existence of widespread efforts. The worldwide priority assessment studies are in themselves evidence that there is no neglect about the importance of this issue. The TAC priorities paper also identified in its plant nutrition section several of the research components as priority areas: biological N fixation, fertilizer use efficiency in humid and semi-arid tropics, multiple sources of nutrients (paragraph 99). The last item also infers the necessity for a more systematic approach to developing effective soil fertility management systems for farmers in developing countries. In the soils and water section (paragraph 102) TAC recognized that additional international support may be warranted in soil characterization and inventories, low input systems for acid, infertile soils, soil and water conservation in rainfed semi-arid areas, and crop tolerance to soil stresses. The same paper (paragraph 90) identified what we call the humid torpics, semi-arid tropics and acid savannas as among the most difficult environments for sustained food production and agricultural development.

1. Soil-plant nutrition as a factor-oriented research. The worldwide priority studies have emphasized the need to consider factors affecting plant nutrition jointly with plant nutrition *per se*. Plant nutrition can be viewed as how to provide and maximize efficiency of nutrient inputs to plants. The authors of this study suggest that consideration of constraints affecting the efficiencies of nutrient inputs might be a more appropriate factor to consider. We would, therefore, suggest that international attention be given to soil-plant nutrition constraints together, with major emphasis on those related to rainfed systems in priority agroecological zones, but without neglecting those occurring in irrigated agriculture.

2. Location specificity. The issue of location specificity must also be addressed. Soil-plant nutrition aspects are sometimes considered so location-specific as to warrant only limited international attention. Cognizance of the

great variability in soil properties at the local level and the need to tailor-make fertilizer recommendations for individual farmer fields has contributed to this belief. The distinction between the kinds of problems and the degree of manifestation of them is important. The priority research components identified for each agroecological zone address kinds of problems that are so widespread and pervasive that they warrant international attention. The degree of manifestation of the problem varies tremendously, hence our emphasis on the need for resource appraisal. Aluminum toxicity, for example, is a widespread kind of problem in the developing world. According to unpublished estimates of the authors, about 1200 million hectares of acid soils in the tropics are aluminum-toxic, which severely affects their crop production potential. The degree of expression of this constraint, however, varies widely not only from region to region, but often from field to field on the same farm. Research on how to alleviate aluminum toxicity via adequate amounts of lime application, selection of Al-tolerant cultivars and the promotion of downward movement of basic cations is of international interest. The use of a liming formula that includes the actual amount of exchangeable Al in the topsoil, the percentage Al saturation and an adjustment for the Al saturation level that the individual crops can tolerate can be used by extension personnel to overcome this constraint at the field level.

Research on how to transfer soil-plant nutrition technology to farmers has been identified as a priority; proper training of soil management specialists to aid this regional and local task is vital. International attention to problems of soil fertility evaluation is warranted as the way to overcome location specificity limitations. In a way, the problems are no different from the ones commodity-oriented IARC's face in producing improved germplasm that has to be tailored to specific regions. Methodology problems have been overcome by those IARC's by a series of means, including widespread field testing by national institutions.

3. Need for international effort. Considering the research needs (Chapter V) and proposed framework (Chapter VI) in relation to ongoing work (Chapters VII and VIII), the authors conclude that though considerable activity is taking place, the magnitude of the effort and the spotty geographical distribution are clearly insufficient to provide a reasonable degree of certainty that technology for alleviating soil-plant nutrition constraints will be adequately developed and transferred in order to permit continuing increases in food production. A strengthening of the worldwide effort is necessary, as has been articulated by the scientists and administrators who participated in the Soil Constraints and Bonn conferences.

The 1979 TAC priorities paper (paragraph 17) stated that "priorities for international research may gradually become the common denominator of national requirements for international activities, which may complement and support their own national research programs." This statement is directly applicable to an international effort on soil-plant nutrition research. It is also relevant to point out that criteria used in assessing priority agroecological zones and the main research components described in Chapter VI are quite similar to the various quantitative and qualitative criteria outlined in the 1979 TAC priorities paper.

The authors, therefore, suggest that international effort on soil-plant nutrition research along the framework outline in Chapter VI, is warranted and necessary to: a) increase the efficiency of plant nutrient inputs, b) increase and stabilize food production in the developing countries and c) conserve the land resource base, particularly in the priority agroecological zones.

The principal international need is to provide a focal point for strengthening, catalyzing and increasing the quantity and quality of soil-plant nutrition research in the crucial agroecological zones of the developing world.

B. The IFDC Issue

Emphasis should be given to the continuation and expansion of IFDC's program on improving fertilizer manufacturing technology for developing countries, improving nutrient utilization efficiencies by combining new or different fertilizer sources with relevant agronomic practices. In these efforts, IFDC occupies a unique role which is providing and should continue to provide critical backstopping and support to present and future soil-plant nutrition research efforts in the developing countries. The authors feel that the current state of improved plant nutrient utilization efficiencies and improved fertilizer manufacturing technologies appropriate for developing countries would not be where they are today nor will they be where they must tomorrow without IFDC. Therefore, the authors recommend that IFDC continue and expand such activities.

C. Institutional Approaches

Three institutional approaches are outlined below as possible TAC/CGIAR actions in soil-plant nutrition research; these range from strengthening existing efforts to specific new initiatives.

1. Strengthen existing IARC's soil-plant nutrition research and establish a network among those conducting such research. The first institutional approach to encourage the strengthening of such efforts by national, bilateral and others in the national organizations, and to establish a network among those conducting such research. This network is regarded by the authors as being limited in scope to the IARC's due to budget constraints. Ideally, it could and would expand to include as full participants the beneficiary countries under a more relaxed budget.

The IARC's have tended to emphasize the location-specific nature of plant nutrition, but not always to approach the problem with the kind-degree philosophy detailed in this paper. It is suggested as future priorities are addressed by the IARC's that soil-plant nutrition research be strengthened and tied together by a network or networks among those performing the research.

The IARC's should be centers of excellence not only in developing improved germplasm, but also in developing germplasm tolerant to adverse soil conditions, and in relating crop performance to soil environmental parameters. Examples of such efforts would be strengthening the CIMMYT breeding attempts to dwarf the Al-tolerant wheat varieties of Brazil, and encouraging the IARC's to increase efforts in characterizing soil constraints as related to their geographical, commodity or farming systems mandates, perhaps along the approach of the CIAT Land Resources Evaluation Program. The TAC (1979) priorities paper also mentioned some specific areas of emphasis such as rice production problems in marginal soils and adaptation of wheat and maize to marginal soil areas, as well as generally more attention of biological N fixation, fertilizer use efficiency, and multiple sources of nutrients. Certainly, strengthening research efforts such as those of IFDC and IRRI for increasing N fertilizer efficiency in flooded rice would be beneficial. This could be accomplished by developing networks along the pattern of INSFFER and others.

Individual CGIAR members should stimulate the increasing involvement of their highly qualified universities and research institutes in cooperative work with national research systems in the developing countries as well as with the IARC's. Such increased collaboration could add depth to the limited personnel presently involved in soil-plant nutrition research at the IARC's and many national research systems.

2. Develop a coordinating center. A second institutional approach consists of creating a coordinating type center under the auspices of CGIAR to catalyze, coordinate and stimulate soil-plant nutrition research in the developing countries. Such a center is envisioned to encompass the institutional approach's actions which have expanded to involve fully the developing countries in order to assist in the evolution of strong national programs, much as those envisioned in paragraph 6.15 of the CGIAR Review Committee's recent report (1981).

The coordinating center concept is not new and has been developing gradually since 1972. Swindale (1980) has reviewed the history of efforts toward an internationally coordinated program for research on soil factors constraining food production in the tropics. The participants at the Soil Constraints Conference resolved that such a coordinating center be established and appointed an international steering committee to further study the idea. The steering committee indicated the following objectives for such a center or board:

a) To strengthen national research capabilities to remove soil constraints to agricultural production;
b) to coordinate and stimulate the application of soil research results already available through transfer of science and technology;
c) to coordinate and promote research on the relationships between land characteristics and crop performance;
d) to enable a sharing of the workload in international soil research and to prevent duplication of efforts;
e) to support and initiate training activities--both at the national and international level--aimed at solving soil-related constraints;
f) to promote the optimization of land use in the tropics, with special reference to soil and water conservation;
g) to identify soil research needs and to mobilize resources to fill gaps;
h) to compile, collate, store, stratify, process, retrieve, translate and disseminate soil research results through data processing systems; and
i) to recommend action on research priorities which are recognized to require urgent action in support of the international endeavor to free the world from hunger.

Considering the complexity and breadth of research components involved, the center would work through international networks each of which would focus on a selected priority. Such a decentralized approach would ensure full involvement of the international research community, allow for geographical coverage and take advantage of resources already available in national and international institutions. The center would be serviced by a small secretariat.

One of the salient features of such a mechanism is that it would build on present capabilities throughout the world rather than requiring major capital outlays for physical plant at a specific location. A small, but well-qualified professional staff would perform the service functions, while most of the field work will be conducted by scientists at different sites along the priority agro-ecological zones of the world. This alternative is embodied in the proposal for establishing the International Board on Soil Resources Management (IBSRAM, 1981).

The potential success of such a coordinating center would be related to the following criteria mentioned in CGIAR's recent review (CGIAR, 1981):

a) Well-defined focus as detailed above;
b) activities are restricted to priority agro-ecological zones;
c) scientifically-strong lead institution which can provide support and continuity for the coordinating center;
d) committed and experienced personnel, including coordinating center director and outposted staff, who can help developa a partnership relationship with scientists in national programs;
e) formal arrangements for participating institutions' involvement made at level of research institution with governmental clearance;
f) each participating institution involved as an equal partner;
g) each participating institution feeling strongly that it gains by participation;
h) each participating institution must have, or be able to obtain from a donor, resources necessary for participation;
i) sufficient funding to bring all participants together for planning and revising the program, for providing the appropriate information and training services.

3. Establish an international soil-plant nutrition research institute. A third institutional approach would be the creation of a major institute with adequate facilities to serve as a center of excellence of soil-plant nutrition research for the developing world. Such a center could be located in one of the priority agroecological zones of the world, preferably where rainfed systems predominate. Neither is this a new idea. Bentley (1978) proposed the creation of such a center, stating the location-specific problems resulting from its location could be overcome by the use of modern methodologies. The TAC study took note of this proposal but did not award high priority to it (TAC, 1979a).

D. Considerations for Evaluating Approaches

The three approaches differ substantially in their nature and level of operation. They are not mutually exclusive. For example, the functions of a coordinating center would include the activities proposed in the first approach. Although TAC has acted on one of them previously, the authors of this report suggest that all be reexamined in light of theproposed framework described in Chapter VI.

Some of the arguments for and against each of the three approaches are outlined as follows:

Approach	Pro's	Cons
#1. Strengthen existing work at IARC's, establish network.	1. Is a modest initial step by the CGIAR to strengthen and integrate soil-plant nutrition research at IARCs, while being cognizant of its current budget constraints.	1. Impact is oriented primarily toward IARCs as participation of national institutions in network will be limited due to modest budget input.

Approach	Pro's	Con's
#1. (continued)	2. Could lead to eventual establishment of #2, the coordinating center, if considered appropriate under relaxed budget constraints.	
#2. Establish coordinating center	1. Is probably the most realistic and perhaps sufficient to overcome main constraints. 2. Includes soil-plant nutrition research efforts by IARCs, national, bilateral and institutional institutes. 3. As beneficiary countries are full partners in program planning plus setting priorities, true partnership develops which will assist in evolution of strong national programs. 4. Involves modest outlays and maintains flexibility. 5. Provides mechanism to link IARC soil-plant nutrition research to that funded by donors through other channels.	1. Implies a new center under CGIAR auspices. 2. Coordination fo such diverse institutions could be difficult.
#3. Establish international institute	1. Creates a full-fledged factor-oriented research center for overcoming soil plant-nutrition constraints.	1. Involves large initial capital and operating costs. 2. May be considered too separate to interact beneficially with other IARCs.

Based on the above considerations, it appears that the most appropriate approach is approach #2, the coordinating center.

The CGIAR (1980) integrative report included a thought in its paragraph 69 that the authors consider a fitting end of this report.

> "Stating the problems of agricultural development is relatively easy. Developing a research strategy in which international, regional, bilateral and national research programs can each play their appropriate role, is fraught with difficulties. No one organization can do it alone nor can it be done at a single attempt. The best that can be hoped for is the development of an institutional framework that will allow a flexible approach to accommodate changing scientific and political conditions."

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Appendix Table 1. Average contents of total reserves, the bulk of which are not directly available to plants, of selected essential nutrients in soils.*

Nutrient	Content
	-kg/ha-
N	3,136
P_2O_5	3,055
K_2O	22,400
Ca	30,688
Mg	11,200
S	1,568
B	22
Cl	224
Cu	67
Fe	85,120
Mn	1,344
Mo	4
Zn	112

* Data adapted from Lindsay (1979).

Appendix Table 2. Annual raw material requirements for fertilizer production, 1980-2000.*

	Developed countries			Developing countries		
	1980	1990	2000	1980	1990	2000
Natural gas (billion m^3)	33.0	60.0	94.5	14.1	36.5	61.3
Naptha (million t)	5.9	7.3	8.6	2.4	3.7	4.7
Fuel oil (million t)	3.0	7.1	12.5	1.3	4.8	8.8
Coal (million t)	6.5	25.0	57.6	2.8	18.3	40.3
Phosphate rock (million t P_2O_5)	29.3	40.6	54.2	10.0	20.4	33.7
Sulfur (million t)	19.2	27.8	38.3	6.5	14.6	24.9
Potash (million t K_2O)	24.6	36.7	51.2	4.5	8.9	14.8

* Adapted from IFDC/UNIDO (1978)

Appendix Table 3. Reserves and production of natural gas, petroleum and black coal in developed and developing regions of the world.*

	Natural gas		Petroleum		Black Coal		
					Reserves		
	Reserves	'76 Production	Reserves	'76 Production	Iden.	Prob.	'76 Production
	----- billion m^3 --------		------ million t --------		-billion t-		--million t --
World	65,875	1,429	87,938	3,959	1,080	8,150	2,210
Developed countries	38,893	1,238	19,773	1,176	740	7,000	1,630
Dev'ed Market Econs. (N.Am., W.Eur., Oceania, Other)	11,987	833	8,720	558	535	2,948	973
Centr. Planned Econs. (E.Eur + USSR)	26,906	405	11,053	618	205	4,052	657
Developing countries	25,982	191	68,165	1,773	340	1,150	580
Africa	5,923	46	8,299	291	6	15	5
Asia and Far East	2,250	28	2,434	116	23	86	95
Latin America	2,558	58	4,604	228	9	36	12
Near East	14,543	59	50,088	1,138	1	2	6
China	708	-	2,740	-	300	1,011	458

* Adapted from IFDC/UNIDO (1978). Reserves as of January 1, 1977, except for black coal which is as of 1974.

Appendix Table 4. World reserves of petroleum and natural gas by country, 1977.*

Country	Oil Reserves Jan. 1, 1977	Gas Reserves Jan. 1, 1977
	million t	billion m^3
WEST ASIA		
Abu Dhabi	3,973	566
Bahrain	40	85
Dubai	205	45
Iran	8,631	9,348
Iraq	4,658	764
Israel	-	1
Kuwait	9,234	898
Neutral Zone	863	142
Oman	795	57
Qatar	781	779
Saudi Arabia	20,550	1,785
Sharjah	4	28
Syria	301	34
Turkey	53	15
Total	50,088	14,544
EAST ASIA-PACIFIC		
Afghanistan	12	78
Australia	189	915
Bangladesh	-	227
Brunei	223	238
Burma	9	4
Taiwan	2	23
India	411	99
Indonesia	1,438	680
Japan	4	59
Malaysia	333	425
New Zealand	26	175
Pakistan	10	448
Thailand	-	28
Total	2,657	3,399
AFRICA		
Algeria	932	3,564
Angola	166	42
Congo Republic	39	1
Egypt	267	79
Gabon	291	71
Libya	3,494	731
Morocco	-	1
Nigeria	2,672	1,246
Tunisia	370	187
Zaire	68	1
Total	3,360	4,019

Appendix Table 4 (Continued).

Country	Oil Reserves Jan. 1, 1977	Gas Reserves Jan. 1, 1977
	million t	billion m^3
EUROPE		
Austria	22	20
Denmark	41	19
France	7	142
Germany (West)	45	212
Greece	5	227
Ireland	-	28
Italy	43	187
Netherlands	12	1,754
Norway	775	524
Spain	60	14
United Kingdom	2,302	850
Yugoslavia	48	42
Total	3,360	4,019
WESTERN HEMISPHERE		
Argentina	315	193
Barbados	-	8
Bolivia	33	142
Brazil	110	25
Canada	849	1,586
Chile	25	56
Colombia	113	142
Ecuador	233	340
Guatemala	3	-
Mexico	1,507	340
Peru	102	62
Trinidad and Tobago	71	97
Venequela	2,092	1,153
United States	4,288	6,232
Total	9,741	10,376
CENTRALLY PLANNED ECONOMIES		
Bulgaria	2	2
China	2,740	708
Czechoslovakia	3	19
Hungary	43	121
Poland	11	124
Romania	294	640
U.S.S.R.	10,700	26,000
Total	13,793	27,614
TOTAL WORLD	87,938	65,881

*Source: IFDC/UNIDO (1978).

Appendix Table 5. World production of phosphate rock by country, 1976.*

Country	Product	Portion of Total
	1000 t	-- % --
United States	44,671	41.8
U.S.S.R.	24,200	22.6
Morocco	15,293	14.3
China	3,400	3.2
Tunisia	3,294	3.1
Togo	2,067	1.9
Senegal	1,796	1.7
Jordan	1,717	1.6
South Africa	1,639	1.5
Vietnam	1,500	1.4
Christmas Island	1,033	1.0
Israel	831	
Algeria	820	
Nauru Island	755	
Syria	511	
India	510	
Brazil	463	
Korea, North	450	
Egypt	443	
Ocean Island	417	5.9
Australia	248	
Mexico	197	
Sahara	173	
Rhodesia	130	
Germany, Federal Republic	85	
Venezuela	80	
Curacao	54	
Sweden	25	
Uganda	15	
Peru	2	
Colombia	1	
Total	106,820	100.0

*Source: IFDC/UNIDO (1978).

Appendix Table 6. World production of phosphate rock by regions, 1976.*

	Phosphate rock
	--- 1000 t ---
World	106,819
Developed Regions	71,434
North America	44,671
West Europe	110
East Europe	24,200
Oceania	2,453
Developing Regions	35,385
Africa	25,227
Asia and Far East	510
Latin America	797
Near East	3,501
Socialist Asia	5,350

*Source: IFDC/UNIDO (1978).

Appendix Table 7. World phosphate reserves and resources, 1977.*

Country**	Total reserves and resources	P_2O_5*** average or range	Country**	Total Reserves and resources	P_2O_5*** average or range
	- million t -	-- % --		- - million t -	-- % --
AFRICA			OCEANIA		
Algeria	1,000	30	Australia	2,000	30
Angola	120	30	Nauru	44	39
Egypt	2,800	30	Ocean Island	2	40
Liberia	1.5	28	New Zealand	70	30
Mali	20	30	Total	2,116	
Mauritania	5	23-32			
Morocco	40,000	30	NORTH AMERICA		
West Sahara	16,600	30	Canada	50	9
Senegal	3,190	30	U.S.A.	38,790	26
Tanzania	10	27-38	Mexico	1,140	30
Togo	300	30	Total	36,790	
Tunisia	1,300	30			
Rhodesia	20	30	SOUTH AND CENTRAL		
South Africa	1,435	10-30	AMERICA		
Uganda	200	30	Aruba	10	30
Upper Volta	4	27-31	Brazil	1,745	30
Zaire	83	15	Colombia	600	30
Total	67,189		Chile	4	30
			Curacao	10	30
WEST ASIA			Peru	6,100	30
Iran	130	30	Venezuela	40	30
Iraq	660	30	Total	8,509	
Israel	1,000	26			
Jordan	1,000	15-30	EUROPE including		
Lebanon	small	17-31	U.S.S.R.		
Saudi Arabia	1,000	30	Finland	225	10-18
Syria	800	30	Ireland	8	25
Turkey	300	30	Norway	100	6-10
Total	4,890		Sweden	no estimate	
			U.S.S.R.	7,125	14-39
EAST ASIA			Total	7,458	
China	15,000	30			
Christmas Island	200	29-38	WORLD TOTAL	144,212	
India	140	17.5			
Korea, North	88	12.5			
Mongolia	1,000	20-22			
Pakistan	12	20-37			
Paracel Islands	20	10-27			
Sri Lanka	300	30			
Vietnam	500	30			
Total	17,260				

* Adapted from IFDC/UNIDO (1978).
** Other countries with small or unidentified deposits include Cameroon, Benin, Gambia, Niger, Gabon, Nigeria, Dahomey, Chad, Cambodia, Malaysia, Taiwan, Japan, Philippines, Indonesia, Belgium, Bulgaria, France, Germany, Greece, Yugoslavia and various South and Central American islands.
*** Those with P_2O_5 averages listed as 30% have been adjusted.

Appendix Table 8. World potash production and reserves by country, 1975-76.*

Country	K_2O production	K_2O reserves
	- 1000 t -	million t
U.S.S.R.	7,944	15,900-24,000
Canada	4,842	18,000-66,500[b]
Germany, Democratic Republic	3,019	4,000-10,000
Germany, Federal Republic	1,950	2,000-9,000
United States	2,220	200-400[c]
France	1,720	200-270
Israel	716	500-2,000[d]
Spain	506	80-270
China	450	no estimate
Congo	278	17-70
Italy	141	200
United Kingdom	34	20
Chile	10	no estimate
Others	5	no estimate
Total	23,835	35,517-112,730[e]

a. Source of production data: British Sulphur Corp., Statistical Supplement No. 14, November/December 1976.
b. Does not include deposits in New Brunswick.
c. Does not include deposits in North Dakota and Montana.
d. Dead Sea, including Jordan.
e. Other deposits not being mined and with no reliable estimate of reserves in Brazil, Ethiopia, Iran, Laos Libya, Morocco, Pakistan, Peru, Poland, Thailand, and Tunisia.

*Source: IFDC/UNIDO (1978).

Appendix Table 9. World production of sulfur (all forms) by country, 1975.*

Country	Production	
	-- 1000 t --	% of total
United States	11,800	22.8
U.S.S.R.	9,460	18.2
Canada	7,420	14.3
Poland	5,040	9.7
Japan	2,400	4.6
Mexico	2,200	4.2
France	1,940	3.7
Spain	1,560	3.0
Germany, Federal Republic	1,070	2.1
Italy	710	1.4
Iraq	600	1.2
Finland	510	1.0
Iran	475	0.9
Germany, Democratic Republic	365	0.7
South Africa	355	0.7
Sweden	266	0.5
Norway	262	0.5
Australia	255	0.5
Others	5,157	10.0
Total	51,845	100.0

* Source: IFDC/UNIDO (1978).

Appendix Table 10. World sulfur reserves and production, 1974.*

	Sulfur reserves			Sulfur production
	Identified	Probable	Total	
	----------------- million t			------------------
Elemental:				
Evaporites	580	100	680	17.6
Volcanic rocks	130	100	230	
Natural gas	155	885	1,040	15.0
Petroleum	265	1,330	1,595	
Pyrites	640	-	>640	11.0
Metallic sulfides	260	>140	>400	8.2
Subtotal	2,030	>2,555	>4,585	51.8
Tar sands	50	>1,800	>1,850	
Coal	20,000	200,000	220,000	
Oil shale		-	280,000	
Gypsum			Vast	
Total	22,000	>200,000	>500,000	

Source: IFDC/UNIDO (1978).